# STEAM BOILERS AND COMBUSTION

JOHN BATEY

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# STEAM BOILERS AND COMBUSTION

BY

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*WITH EIGHTEEN DIAGRAMS*

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# PREFACE

Some explanation is probably expected for the introduction of another book on such an apparently hackneyed subject as Steam Boilers; yet this work may be more necessary to-day, in spite of the large number of treatises extant, and the deduction is reasonable when so many scientists and professional engineers are engaged in the laudable purpose of seeking improved methods to gain a higher efficiency in practice.

Unfortunately most of the books published are highly technical works dealing with what has been done and not with the possibilities of future development. This spells a great danger to initiative—which is discounted to a great extent—by placing too much reliance on the past rather than encouraging a determined attack on future possibilities.

A learned professor has gone farther than most in this direction when he asserted that engineers and boiler experts had been fostering wrong ideas in spite of the fact that extended practice qualified present laws. His declaration that the theories accepted, and their laws, were utterly wrong, is a deduction from what his own experiments revealed.

Credit is due to him for his courageous pronouncement, and no one doubts the sincerity of his intentions, yet it may be that his professional zeal carried him farther than he really intended.

That he attained a much higher quantitative efficiency than was usual to ordinary practice there can be no question; but there may be a suspicion that his enthusiasm led him astray when he attributed effects to causes that may be erroneous.

In pursuance of a purpose, problems of combustion will be examined, and as far as possible cause will be traced back from effect, and the causes will be referred to well-known effects as a comparison. Principles, as accepted, will not be descried, though their application may sometimes be questioned.

All analysis will be based on recognised science, and results will be compared with authorised deductions, and any comparative performances will be those that have received publicity through the pages of the Engineering Press, or are embodied in the pages of the reports of Scientific Societies.

So far as the writer knows, no work of this character, as outlined, has been published; yet attention must be called to Mr. C. W. William's work, which so many years ago received much well-merited attention in spite of its highly technical character.

That work was more in the nature of an analysis of chemical science in regard to combustion, whereas the present purpose is a desire to incite ingenuity to throw off all restraining trammels, with the intention of trying to stop the tremendous waste now going on in the majority of steam plants throughout the world.

JOHN BATEY.

COVENTRY, *April*, 1915.

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# INTRODUCTORY AND RETROSPECTIVE.

STEAM boilers are relatively safe when they are carefully worked under reasonable conditions and are the product of reliable manufacturers.

Accidents occasionally occur, but most are traceable to gross ignorance or culpable negligence.

Sometimes the best managed plants—the product of some well-known maker—made to the most up-to-date design, and apparently worked under expert conditions, come to grief, and often spread disaster.

When installing new plant it is a wise course to allow a considerable margin for growing demands; but under no circumstances should evaporation be forced at the expense of safety; besides there is no wisdom in producing large quantities of steam when wasting valuable fuel.

It is desirable that all steam plants should be insured in a responsible Boiler Insurance Co. whose inspectors make careful and periodical examinations, and outside inspection pays even where the staff and management are extra capable and efficient.

Outside control rids the management of a serious responsibility, and relieves an already busy man of the danger of running his plant too near to the danger zone.

The more capable the man, without outside control, the more likely is the plant under his care to be

run too close to its safe limit, merely because he knows the margin and is satisfied so long as the limit is not reached.

To know all about the strength of a boiler is wise, yet a calamity may actually be invited by the very knowledge that should prevent it.

Where a boiler plant is insured the premiums paid should be ample to allow for efficient and regular inspection, and the Insurance Company should be strong enough to insist upon attention to their reasonable demands.

Perhaps no greater safeguard to ensure safety and long life to any steam plant is circulation and cleanliness.

Periodical inspection ensures cleanliness and careful scaling, and any outlay expended on obtaining pure water for evaporating purposes well repays the initial outlay.

Board of Trade rules generally err on the safe side, therefore they should be strictly adhered to.

The production of steam involves so many delicate processes, that the neglect of some simple item may result in untold mischief.

Economy is a relative term and is of relative value, because it includes not only saving fuel, but saving expense.

To save a few hundredweights of fuel, whilst adding enormously to the initial cost of the plant, is unwise economy; whereas to save fuel, and increasing the quantitative efficiency of a relatively small boiler plant, costing relatively much less than the usual plant, is wise economy, and good practice.

The employment of men who are physically able

to shovel coals into the open mouth of a furnace, and to pay them accordingly, may reduce the wages bill, but the yearly expenses suffer. The employment of brainy stokers may add to the wages bill, but the yearly accounts will, or should, allow for it and leave a good margin of profit.

Where, probably, 50 per cent of the possible energy derived from the use of coal is absolutely wasted, there is, and should be, ample room for improvement; and it is the duty of all steam users to attend to a matter which is at once personal and national, because attention to details must eventually end in a much better use of fuel energy.

# CHAPTER I.

## COMBUSTION AND STEAM PRODUCTION.

Two classes of heat, or rather distributions, are natural to the vaporization of water, viz. sensible and latent heat.

Sensible heat, which is the heat used in heating the water up to its evaporation temperature, is indicated by the thermometer, and latent heat is conditional to the evolution of steam.

For each pressure saturated steam has a given temperature which implies the presence of a definite heat value, usually referred to a unit weight of water or steam, and it is known that 1 lb. of fuel, of an estimated heat value, referred to B.Th.U. terms is capable of evaporating a given number of pounds of water.

But where 1 lb. of such fuel can evaporate 10 lb. of water under a pressure of 65 lb. per square inch, it does not mean that 10 lb. of water can be evaporated under a pressure of 200 lb.

In the first case it involves the use of 11,720 B.Th.U. and in the latter 11,978, assuming that both are from 32° F.; therefore, as the pressure is increased the quantity of water evaporated decreases for equal quantities of fuel burnt.

*Sensible Heat.*—This heat, as indicated by the temperature, indicates that heat is present in a sub-

stance, but temperature does not measure out the quantity of heat the substance contains, because the same temperature exists in a unit quantity as in any larger volume, however great. Yet for a given weight of a given substance the temperature is an indication of the sensible heat.

As heat is applied to water the temperature rises to 212° F. under atmospheric conditions; but beyond 212° F. the thermometer shows no indication by its increase, because it continues at one temperature although heat is continuously applied, but the temperature will rise if the pressure is increased.

Under 14·7 lb. per square inch (atmospheric pressure) the temperature of steam, under usual barometric conditions, is never beyond, or less than 212° F.; whereas under 400 lb. pressure the temperature is raised to 444·9° F., and supposing no conditional alterations occur at 1000 lb. pressure the sensible heat will be 546·5° F.

Generally, amongst steam users steam pressure is looked upon as a matter of simple convenience, or high pressure means a smaller plant, presumably costing less money and occupying less space than that required for a less pressure; but it means more than this, inasmuch as the higher pressure carries with it certain heat advantages which tend to economy.

The temperature for 200 lb. per sq. in. (absolute) pressure is 381·7° F. and for 100 lb., 327·9° F.; or a difference of 53·8° F.

The latent heat for 200 lb. = 844, and for 100 lb. = 883 units (B.Th.U.), or a difference of 39 units.

The total heat of the steam is the sum of the

sensible and latent heats, so that the difference in total heat in the two cases is about 35 B.Th.U., i.e. one pound steam at the higher pressure contains 35 more units of heat than at the lower pressure.

*Combustion.*—Fuel burnt in conjunction with dry atmospheric air is said to suffer combustion, and the process may be economical or otherwise, according to circumstances and conditions; and as both are contingent upon human agency—whether applied direct, or through the agency of machinery—man is the arbiter of the extent to which combustion is utilized to a good or bad purpose, as an energizing effect or factor. This important phase in boiler practice will receive attention, warranted by its importance, in succeeding chapters.

*Heat of Combustion.*—Two classes or kinds of heat are derived from the combustion of fuel, namely radiant and convected heat. Though both are obtained from the same substance they are independent of each other; yet they can act in conjunction, or give off separate effects, according to conditions.

Radiant and convected heat need not have the same heat quantity value—though both are produced under one temperature, and both are influenced by the quantity of air associated with the combustible. Radiant heat acts direct from its source, and acts without raising the temperature of the medium through which it passes. Convected heat is the heat carried by the particles of air, and has a much wider range of action than the other, because it is carried by current from place to place, and by conduction it is capable of transferring heat to surfaces

a long way from the source. By such means the water in a boiler is influenced by the heat derived from the gaseous products, though it may be at some distance from the fire.

Radiation of heat always takes place wherever heat is present, and its contiguous neighbour receives the benefit when it is of lower temperature than its hotter neighbour; but radiant heat is limited in its range and also in its source supply, being that of the surface from which it emanates.

Radiant heat thrown off from the surface of burning fuel may be likened to needles of heat moving at considerable initial velocity, and losing speed as the distance from the source increases.

In the short distance between the surface of the fire and the metal surface above it in a tubular boiler its effect is enormous, and generally radiant heat is credited with the evaporation of 50 per cent of all the water evaporated where radiant heat is intercepted by suitable heating surface. Roughly speaking where a surface of 1 square foot is heated by radiant heat from a given quantity of fuel, then 125 square feet of surface can be assigned to convected heat associated with the combustible gases.

In boilers of the Lancashire type, where the furnace is part of a tube length, the average distance from the surface of the fire to the heating surface above it may be 1 foot, and by the law of inverse squares at 2 feet away the effect is one-fourth of that at the surface; the proportionate values of the two heats are, for equal quantities, 1 for radiant and one-sixtieth for convected. This rough valuation is what practice teaches, but the ratio is

contingent on the position of the heating surface under radiant heat effect. Temperature has a great influence on relative quantity, but radiant heat compared with convected is lower proportionately as the temperature is increased. Yet in ordinary practice, probably, the two heats are roughly equal in regard to quantity. Now radiant heat has no direct influence on a gas though it may have, under circumstances—due to conduction from the surface; but radiant heat generally attacks a surface that does not get rid of its heat quickly to the water in contact.

Unfortunately, all the radiant heat given off from a fire surface cannot be used for evaporative purposes—though in practice the furnace-heating surface probably accounts for from 40 to 50 per cent of all the water evaporated in any one boiler. In Lancashire or Cornish boilers, and in locomotive boilers, radiant heat by direct action and by conduction induces evaporation. This is especially noticeable by the high efficiency of the first few inches of tube surface in the locomotive boiler, and the first few feet beyond the bridge in the fire tube type.

*General Observations.*—The products of combustion transfer heat from one particle to another, but each particle, as it assumes the condition of a gas above the fire, must take heat from the fire; yet it is known that a hot gas will impart heat to a colder, though it takes time to produce a result, and from this it is safe to assert that gases part with heat very slowly. And that is why such large surfaces are given to get the heat out of the gaseous volume obtained from the combustion of fuel.

Therefore time and surface are factors in obtaining

high efficiency from any boiler; but there is a limit where it is uneconomical to provide surface to get extra evaporation, because the cost of supplying the surface may be much more than the value of the heat extracted. Draught is another necessary factor on which rests temperature of fire, and the economical distribution of convected heat.

Some boiler-users imagine that a roaring chimney indicates a good draught. It is true; but it is a wasteful one and should not be permitted, because it is a proof that the gases are moving at a fast speed over surfaces exposed to it, and heat is transmitted at a less rate than if the speed of flow was less.

The accepted theory is that a slowly moving gas gets rid of more heat in a given time than a quicker movement could do. Some, such as Professor Nicolson, take a contrary view; but a very homely illustration disputes the assertion of the advantage of a high velocity.

A hand allowed to rest above the flame of a candle soon produces the sensation of burning, whilst the hand moved at a rapid rate, in the same plane, loses all sense of sensation of heat.

Substituting a thin, shallow dish containing water for the hand, the water is soon evaporated if the dish is stationary; but moved above the flame quickly it will take a long time to produce evaporation by heat.

Whether the dish is stationary or not the same value of heat is given off by the candle flame in equal times, the only difference is that the stationary condition intercepts more heat for the water than when the dish is moved over the flame at some speed.

In the first case heat is associated with the water

to a greater amount than when moved above the flame rapidly, when the water receives little heat and the air a great deal. In a similar way the velocity of a gas through the flues of a boiler influences evaporative efficiency.

Experiment and extended practice show that between 400° F. and 600° F. temperature of the chimney gases the velocity of outflow from the chimney is practically equal, and this may be taken advantage of to a good purpose.

The volume of any gas bears a proportion to the absolute temperature for one weight of gas; therefore the gas of a lower temperature is heavier per unit volume, and this extra weight has an influence on the speed of the gas through the flues.

If the products of combustion equal so many lbs. of gas, when the chimney temperature is 600° F., the boiler will give a certain efficiency; but if the gases in the flues are put under pressure, until the leaving temperature is that of the chimney, the excess temperature due to compression increases evaporation, because more heat is transmitted in a given time.

Compression reduces the volume and increases the temperature, and the gas, due to its reduced volume, has a lower speed over a given time, and with a reduced volume the outlet to the chimney can be reduced. When the reduced volume passes the outlet and expands to atmosphere, the heat held is spread over the increased volume and the temperature falls.

Now reduced velocity is an advantage, in that a given volume subjected to compression is reduced

and it traverses a given flue in a longer time, and this is in favour of heat transmission; thus an extra efficiency is gained.

A pressure of a considerable amount is possible in boiler practice with a chimney temperature of 400° F., but a better result is possible for a chimney temperature of 415° F., whereas very little better result can be obtained by a temperature of 600° F., therefore it is wasteful to use it. This and other effects will be taken into consideration at a subsequent stage; but a few general remarks on conditions to be observed in boiler practice will be of advantage at this stage.

Keeping the water level at a non-priming height, and using clean water in a clean boiler will be found of advantage even in a boiler where the steam space is restricted. Priming is largely preventable, whilst a continuous feed even for ordinary boilers gives comfort and economy; besides it equalizes the strains a boiler is subjected to by intermittent feeding. Circulation is as necessary to a boiler as it is to the human body, and should receive as careful attention. Moreover, so little is required to disturb the direction of movement that every care must be taken to encourage the right movement in the direction required.

Natural circulation rests upon the narrow foundation of different weights for equal columns of water. The heavier displaces the lighter, yet the difference may be so slight as to be scarcely definable; still it is sufficient to ensure circulation.

Allowing water to dwell on a hot surface is wasteful, because water transmits heat very slowly com-

pared with metals, and as a general statement it may be assumed that the metal surface will transmit heat as fast as it receives it, the rate being merely controlled by the water.

Water is such a poor conductor that it is possible to boil off three inches of water above ice without the latter suffering, and on the other hand hot water will not sink; therefore the greatest care is needed to ensure constant circulation.

*Circulation.*—When all the water in a vessel is raised to the boiling-point vapour is given off rapidly, and as the lower strata is hottest it rises to the surface, causing ebullition or bubbling.

The water must be colder than the vessel, therefore fluid in contact with the sides and bottom is heated more rapidly than the middle bulk. As the water at the side rises some overflows the envelope, and the other part tumbles over to the centre, and this is the chief reason why an open pot boils over.

If one vessel is inserted within the other, leaving a hole on the bottom of the inner vessel, the fluid contained between the two walls heats rapidly, and as the colder water sinks and passes through the hole in the bottom circulation is set up, and more water can be boiled off in a given time by the double vessel than by the single; therefore the method is economical.

Perkins, in 1831, adopted the method, and much later Field.

The Field-tube boiler proved an advantage over other boilers of its type, by being more economical and producing more steam in a given time for equal space occupied.

These and many other matters will receive extended attention in due course.

# CHAPTER II.

## USEFUL AND NECESSARY INFORMATION IN REGARD TO BOILERS AND MATTERS CONNECTED WITH THE PRODUCTION OF STEAM.

TEMPERATURE of the surface of the fire is important, because the rate of heat transmission rests upon the difference of the temperature on the opposite sides of the transmitting plate.

As no thermometric indication is possible by the ordinary thermometer, various methods are used to determine the value: by pyrometers, or by the capability of melting known substances whose melting-points are known; but like many other things in steam boiler practice the appearance of the fire is resorted to as a sight test, and to aid this test by colour the following grading is given, and the about temperatures are :—

| | | |
|---|---|---|
| Dull red | Temperature | 1260° F. |
| Cherry ,, | ,, | 1460° F. |
| Bright ,, | ,, | 1650° F. |
| Brilliant ,, | ,, | 1830° F. |
| Orange colour | ,, | 2000° F. |
| White heat | ,, | 2300° F. |

The sight test is of little value, except to tell the general state of the fire, because a very few degrees influence the quantitative value of radiant and convected heat; whilst the fusion tests are merely approximations, because the actual heat is never

determined, due to the shielding of the material by the vessel holding it.

| | | |
|---|---|---|
| Lead melts | at | 561° F. |
| Antimony | „ | 810° F. |
| Copper | „ | 1996° F. |
| Cast iron | „ | 2012° F. to 2786° F. |
| Steel | „ | 2372° F. to 2552° F. |

The copper test is the one likely to be most useful, although the furnace temperature capable of melting the copper is likely to be much more than 1996° F., because the receptacle in which the copper is placed absorbs heat and radiates much back to the fire; therefore the melting-point is only approximately near to the actual temperature of the fire.

As the temperature of the fire surface is important, the subject will receive attention in due course.

*Horse-power of a Boiler.*—To know the horse-power of a boiler enables a comparison to be made with boilers of a similar type; but the only true test of any real value is evaporation. Now evaporation is contingent upon the estimated heat value of the fuel and the amount burned per hour; but different boilers have varying proportions of fire-grate surface and heating surface, and varying rates of evaporation.

For instance five types of boilers are given, and all have different proportions referred to 1 horse-power.

| | Square feet of heating surface per h.p. | Grate Area per h.p. | Rapidity of evaporation in relative terms. |
|---|---|---|---|
| Vertical . | 10 sq. ft. | ·400 sq. ft. | 0·50 |
| Water Tube | 11 „ | ·300 „ | 1·00 |
| Locomotive | 14 „ | ·275 „ | 0·85 |
| Scotch . | 16 „ | ·250 „ | 0·91 |
| Flue . | 17 „ | ·250 „ | 0·60 |

The above values are mere approximations; still they are useful as a rough guide to purchasers and users, and to further simplify comparison the ratio of fire-grate to heating surface for the five types are as follows, given in the order of the preceding table:—

| (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|
| 1 to 25— | 1 to 36·6— | 1 to 50— | 1 to 64— | 1 to 68 |

From such data the designer is able to ensure a given evaporation from the combustion of a given quantity of fuel of an estimated heat value; whilst the purchaser gets what he asks for within reasonable limits, and the user uses his best endeavours to get the power the plant is assumed to represent, and if he gets more he is abundantly satisfied.

Whilst these assertions are true in substance, the fact remains that many plants supply so much power beyond that estimated that they add to the numerous boiler problems still extant.

*Heat Value of Fuels.*—Heat value in fuels varies from 16,214 to 9000 B.Th.U. per lb., which makes it necessary to have some idea of the real value before the horse-power of a boiler can be determined. For convenience three classes of coal are referred to because they are in general use, viz. Welsh, English, and Scotch. The first is described as anthracite, and the two latter bituminous, in which the English averages 80 per cent of carbon, and the Scotch 78 per cent.

The estimated average B.Th.U. values of the three kinds are:—

| | | |
|---|---|---|
| Welsh | 15,230 | B.Th.U. |
| English | 14,133 | " |
| Scotch | 12,870 | " |

but a very usual value is 14,700 B.Th.U. per lb. of average good coal, which is a mixture of Welsh and bituminous, being the quality usually affected by locomotive and marine users.

Whilst it is true that 1 lb. of average coal will give 1 horse-power under special conditions, in general practice from 3 to 4 lb. are the more likely figures.

*Water.*—Water is just as necessary as fuel to the steam boiler, therefore some of its equivalent proportions are given. The weight of a cubic foot of water varies from 62·4 lb. to 59·76 lb.; the first taken at 32° F. and the latter at 212° F., or in cubic inch terms, from ·03612 cubic inches at 32° F. to ·03458 at 212° F.

The imperial gallon equals 277·274 cubic inches, and weighs 10 lb. taken at 62° F. equal about 6¼ gallons, or 62·5 lb. per cubic foot, whilst sea water is 64 lb. fully per cubic foot at 62° F.

A column of fresh water standing on an area of 1 square inch and 2·309 feet high, weighs 1 lb. at 62° F. Usually all chimney-draught pressures are referred to inches of water, therefore as 1 lb. per sq. in. corresponds to 27·71 inches of water, so 1 inch of water gives ·036 lb. or ·576 oz. per sq. in. at 62° F.

## CHAPTER III.

### WATER AND STEAM.

*Water Purifying or Softening.*—Water generally contains some foreign matter, relatively exceedingly small compared with the water volume, yet sufficiently large when tons of water have passed through a boiler, when the aggregation of these minute particles assume alarming proportions, and some method must be employed to get rid of them, or to reduce the quantity to a harmless point.

Fortunately water parts with all its impurities when converted into steam, and water readily absorbs other substances which can be used with advantage, and at 320° F. lime salts are nearly all rejected. With this and other knowledge water purifying or softening becomes a simple matter.

To attempt to enumerate all the specifics which claim to rid water of its impurities would represent an enormous task, besides serving no useful purpose. Moreover, water is something like the human body; one specific may be good for one person, but bad for another; thus water calls for more or less expert handling if real good is to ensue.

"Tannate of soda" is a common specific, and will generally suit most water except when sulphate of lime is present; then carbonate of soda, or soda ash, will be required.

The chief aim of all softening methods is to prevent the foreign ingredients settling on the plates as scale; therefore reducing the impurities to sludge—which can be blown off—removes one of the chief difficulties in regard to matter in suspension.

Hardness of water is generally due to the presence of lime salts and these are more difficult to deal with.

Placing a wicker basket full of lime about a foot below the surface in a hard-water tank, adds excess of lime by actual contact, and this overloads the lime in the water causing it to be precipitated; therefore, if the feed is taken from near the surface this simple method will effect the purpose, perhaps, better than a more elaborate contrivance; of course the lime must be renewed, but observation will generally indicate the time.

Whilst hard or impure water is to be condemned, very soft water is equally condemnable, and if persistently used the boilers will begin to leak badly.

In all cases clean and relatively pure water will repay any reasonable outlay to obtain it.

In all cases it is best to enlist the service of the chemist, and in large establishments a qualified chemist should be on the permanent staff to analyse and examine all water and gases, and in all cases the expenditure will be more than recouped by the saving effected.

*Standards of Comparison.*—Such have been provided by men of unquestioned ability, whose labours over many years have not been discredited.

Scientists have given specific heats and specific gravities as standards of comparison for various substances. The standard for water is 1·0, and until

recently the specific heat of saturated steam was standardized as ·305, and superheated steam as ·475, now taken as ·48.

The first determination for saturated steam is Regnault's; but more recent experiments have been carried out with better apparatus, and in opposition to his idea "that the specific heat remained constant," it has been found that the specific heat increases with the temperature; but these advanced theories are not universally accepted, therefore the older and more widely accepted value is taken, viz. ·305 as the specific heat of saturated steam.

It is quite reasonable to assume that steam saturated with moisture is nearer the liquid form than superheated, and it should be nearer the specific heat of water than that of steam practically free from moisture.

Superheated steam is obtained by adding heat to isolated saturated steam, which increases its temperature and presumably reduces the proportion of moisture. Thus saturated steam should have a greater specific heat than superheated, which is ·48; whereas the specific heat of saturated under the old law is ·305.

This value is used in this connexion, not because it is assumed to be more correct than the latest valuation, but merely because most steam tables are based upon it.

Professor Smith in a recent work gives a formula for finding the total heat of saturated steam which fits closely with the heat tables given by Marks and Davis, but no more can be said for it than "that it suits the table".

The formula referred to is

$$H = 1826 - t - \frac{1,250,120}{1020\ t}$$

where $t$ is the temperature of the steam in ° F. and H. in B.Th.U.

All physicists agree that each pressure has its own particular temperature and total heat value, though the total does not follow in any definite proportion to temperature; but there is a very definite drop of latent heat as temperature and pressure rises.

The table of steam values appended is merely to aid the work of reference if needed. It is merely a copy from existing steam tables, and there is no intention of entering the field of controversy in regard to their accuracy because it is full of pitfalls and pregnant with doubtful factors. The only purpose is convenience of reference, to enable readers to consult a steam table without turning to another book unless there is special need.

The condensed form is assumed to be sufficient for the purpose intended (see opposite page).

In all tests conducted with steam boilers the thermometer is a necessary instrument, and that of the Fahrenheit scale is the one generally referred to it in Great Britain.

STEAM TABLE.

| Absolute Pressure per Square Inch | Temperature in F. Degrees | Total Heat from 32° F. B.Th.U. | Latent Heat F. B.Th.U. | Weight per Cubic Foot | Volume of 1 lb. Steam | Relative Volume to Water |
|---|---|---|---|---|---|---|
| 1 | 102·1 | 1112·5 | 1042·0 | ·0030 | 330·36 | 20,600 |
| 5 | 162·3 | 1130·9 | 1000·3 | ·0138 | 72·66 | 4,530 |
| 10 | 193·3 | 1140·3 | 978·4 | ·0264 | 37·84 | 2,360 |
| 15 | 213·1 | 1146·4 | 964·3 | ·0387 | 25·85 | 1,611 |
| 20 | 228·0 | 1150·9 | 953·8 | ·0507 | 19·72 | 1,229 |
| 25 | 240·1 | 1154·6 | 945·3 | ·0625 | 15·99 | 996 |
| 30 | 250·4 | 1157·8 | 937·9 | ·0743 | 13·46 | 838 |
| 35 | 259·3 | 1160·5 | 931·6 | ·0858 | 11·65 | 726 |
| 40 | 267·3 | 1162·9 | 926·0 | ·0974 | 10·27 | 640 |
| 45 | 274·4 | 1165·1 | 920·9 | ·1089 | 9·18 | 572 |
| 50 | 281·0 | 1167·1 | 916·3 | ·1202 | 8·31 | 518 |
| 55 | 287·1 | 1169·0 | 912·0 | ·1314 | 7·61 | 474 |
| 60 | 297·2 | 1170·7 | 908·0 | ·1425 | 7·01 | 437 |
| 70 | 302·9 | 1173·8 | 900·8 | ·1648 | 6·07 | 378 |
| 80 | 312·0 | 1176·5 | 894·3 | ·1869 | 5·35 | 333 |
| 90 | 320·2 | 1179·1 | 888·5 | ·2089 | 4·79 | 298 |
| 100 | 327·9 | 1181·4 | 883·1 | ·2307 | 4·33 | 270 |
| 110 | 334·6 | 1183·5 | 878·3 | ·2521 | 3·97 | 247 |
| 120 | 341·1 | 1185·4 | 873·7 | ·2738 | 3·65 | 227 |
| 130 | 347·2 | 1187·3 | 869·4 | ·2955 | 3·38 | 211 |
| 140 | 352·9 | 1189·0 | 865·4 | ·3162 | 3·16 | 197 |
| 150 | 358·3 | 1190·7 | 861·5 | ·3377 | 2·96 | 184 |
| 160 | 363·4 | 1192·2 | 857·9 | ·3590 | 2·79 | 174 |
| 170 | 368·2 | 1193·7 | 854·5 | ·3798 | 2·63 | 164 |
| 180 | 372·9 | 1195·1 | 851·3 | ·4009 | 2·49 | 155 |
| 190 | 377·5 | 1196·5 | 848·0 | ·4222 | 2·37 | 148 |
| 200 | 381·7 | 1197·8 | 845·0 | ·4431 | 2·26 | 141 |

Three scales are in general use: Fahrenheit, Centigrade, and Reaumer, and it is convenient at times to be able to convert the one into the other; therefore the rules are given as under:—

To convert Centigrade into Fahrenheit:—

Rule—Multiply Centigrade by 9 and divide by 5 and add 32.

To change Fahrenheit into Centigrade :—

Rule—Take 32 from the given temperature, and divide the remainder by 9 and multiply by 5.

Centigrade to Reaumer : $\frac{R \times 5}{4} = \text{Centigrade}$.

To change Fahrenheit into Reaumer :—

Rule—Take 32 from F. temperature, and multiply the remainder by 4 and divide by 9 and the quotient is Reaumer value.

The formulas for each are :—

$C = \frac{5}{9}(F - 32)$. $R = \frac{4}{9}(F - 32)$. $C = \frac{5}{4}R$.

Considerable looseness of expression is used when referring to temperatures and specific heat. In this work specific heat means the heat value needed to increase the temperature of a unit weight of substance 1° F.

Further the B.Th.U. value is that amount of heat required to raise the temperature of 1 lb. of water from, say, 39° to 40° F., and is equivalent to 772 foot-pounds of work, by Joule's early experiment or 778 the latest determination.

*Superheated Steam.*—When saturated steam is isolated from the water of its formation, and charged with further heat, it is said to be superheated.

Adding heat in this way increases the volume under a constant pressure, and according to Regnault's determination ·475 units per lb. weight of steam is required to raise the temperature 1° F. Suppose (saturated) steam of 250 lb. pressure per square inch has heat added to it when isolated until the temperature is 840° F. the original volume is increased nearly one-third ; or by adding 440° F. to 401·1° F. the volume is increased nearly one-third

and the steam is assumed to be changed into a perfect gas, when other additions of heat will only influence it as if it was air.

One point is important, that is when saturated steam at 212° F. is raised to 230° F. or through 18 degrees, the expansion is 5 times that of air for an equal addition of heat, and from this determination Dr. Siemens from actual test asserts that above 230° F. the expansion of steam is uniform, even as that of a perfect gas.

Another point is worth noting in this connection, which is proved by practice, that to get double the temperature of say to 800° F., 1600 heat units are required. Dr. Siemens' determination is generally accepted, viz., that an addition of 20° F. makes saturated steam practically gaseous.

## CHAPTER IV.

### STEAM BOILERS.

STEAM boilers are merely sealed vessels in which water is evaporated under pressure to as much as 300 lb. per square inch and more. They are provided with furnace, flues, water, and steam space, an outlet from the steam space and another for the waste gases.

These vessels, by continual operations, need the use of pumps, injectors, or other means of keeping up the water supply.

Geared pumps driven by the engine represents one of the surest and cheapest methods when the water is pumped through a heater to raise its temperature to 200 F. before being forced into the boiler. Such heaters are usually heated by the exhaust steam which costs nothing, though it is only available when the engine is at work.

Live steam, taken direct from the boiler, is frequently used, for which many advantages are claimed by makers of live steam feed apparatus, but whether this claim can be substantiated or not is a matter for users to determine.

Injectors are very commonly used, but they are not nearly so economical as pumps, though makers claim that they are, in spite of what practice teaches

when the water is forced through a heater before entering the boiler.

Whatever other claim may be made there is no need to question the convenience of injectors, because economy sometimes must give way to conditional convenience. The choice of apparatus for feeding water to a boiler is best left to those who have to decide, but no question can be raised against the superiority of supplying a boiler with hot water instead of cold.

Convenience and utility are prime factors in boiler matters, and much difference of opinion exists as to what is best. Where salt water is used a common practice is to encourage a coating of scale on all heating surfaces as a preventative to pitting caused by acids.

In marine practice it is generally allowed and it has much to recommend it, in spite of the fact that it is opposed to fuel economy.

No scale should be permitted except under very exceptional conditions, because it easily becomes a menace and danger; therefore other methods should be used to prevent pitting. Clean surfaces, free from scale, allow more heat to get to the water, because scale is as hard as adamant, and it causes a great loss because fuel is burned to no useful purpose, and boiler evaporative efficiency is greatly reduced.

Sea water is particularly dangerous as a pitting agent, and engineers favour a slight scale deposit, though they know it is opposed to fuel and evaporative economy. Such deposit sometimes insidiously gathers in such quantity, and forms such a heavy coating, that the heat is unable to get to the water,

whereby the flues get so hot as to allow the pressure to distort them inward, and it is no uncommon matter to have a furnace crown bulge inwards, where scale-deposit has been allowed to become too thick.

In many boilers scale-deposit rapidly occurs, though it is generally due to carelessness and want of attention.

When such does occur scaling becomes nearly an impossible operation, and more drastic measures must be used to free the boiler from the incrustation.

The use of caustic soda is frequent, and in cases that are excessively bad the scale may be removed by injecting about 4 ounces of caustic soda per boiler horse-power, with the feed; this will dissolve the scale or rather loosen it. But in all cases the boiler should be blown down and the scale cleared away, and afterwards the boiler should be thoroughly washed out, or serious pitting is likely to occur.

The boiler should be out of action when the solvent is used, but scaling and thorough washing the inside is necessary in all cases.

*Loss of Heat from Surfaces Exposed to the Air.*—When a boiler surface is exposed to the usual atmospheric conditions, about 4·5 units of heat are dispersed for every degree of difference between the steam and air temperatures per square foot of surface per hour. Where the inside temperature is 300° F. the loss per square foot per hour is equal to about 1350 B.Th.U. Therefore all exposed surfaces should be efficiently covered with non-conducting material to prevent excessive radiation. Generally, boilers are enclosed in a boiler room, when the loss is only about one-

third of 4·5 units. Still it is sufficient to mean a serious loss where large boiler surfaces are left uncovered.

The same remarks apply to steam pipes, steam-engine cylinders, and valve chests, all of which should be clothed to mitigate the loss.

Most boilers are enclosed in rooms, so it is necessary to ensure a constant supply of cold air to the ash-pits, because it is most economical to use air at its lowest normal temperature. As air is an essential factor in all boiler installations, its weight, pressure, and volume enters into all calculations in boiler practice.

Generally, the mean atmospheric pressure is taken as 15 lb. per square inch, though the actual pressure at 32° F. is 14·7 lb. A column of air standing on one square inch reaches to a height of 21,404 feet, and results in 14·7 lb. pressure.

Air is about $\frac{1}{773}$ times the weight of an equal volume of water at 32° F. and $\frac{1}{772}$ at 62° F., therefore the normal average atmospheric pressure can safely be taken in calculation.

If air pressure is referred to a column of one square inch the height is 21,404 feet, and is comparable, by weight, with a column of mercury 30 inches high, and a column of water 384 inches high—each weighing 14·7 lb.

These values will be found useful at other stages of the work.

The vessels in which water is evaporated are of many forms, and endless books have been written which deal with proportion, construction, strength and character of materials, weight, etc., and those who

wish to look closely into such details are referred to the literature provided for necessary and useful information, because the present purpose is to deal only with the effects produced by the application of heat to steam generators.

In regard to steam boiler possibilities nothing like finality has been reached, or nearly approached, in spite of vast experience, and abundant knowledge.

No one is able to say with any degree of certainty what the greatest economy should be, or the quantitative efficiency of any boiler, for a given size.

One indisputable fact is ever before our eyes, which supports the contention of want of accurate knowledge, namely the dense atmosphere of smoke that covers our manufacturing centres, and not until this nuisance has been abated, by ensuring combustion without the unnecessary evolution of smoke, can it be said that the practical state of perfection has been reached.

Unfortunately, opinions widely differ even amongst professional exponents; because some contend that the evolution of smoke is necessary to economy, whilst others assert that strict economy cannot occur where smoke is abundant.

In regard to the smoke question we are little better off than the people of sixty years ago, and this is in spite of innumerable contrivances of inconceivable variety that have been exploited, with the set purpose of eradicating the evil.

To-day the conditions are changed, in that instead of dense volumes over a short time we have a continuous outpouring of less dense volumes over

a long time. The trouble has merely been spread out, but the quantity remains practically the same. Another startling fact is forced upon us when some catastrophe to a boiler occurs, and the cause is enveloped in mystery.

Frequently the most serious explosions are from plants that are the product of some well-known and acknowledgedly capable firm, which plants were officered by expert and really capable men. In fact explosions occur in spite of the most up-to-date appliances.

After the explosion the best experts are frequently nonplussed in regard to the prime cause of the disaster.

With such facts pressing upon the public mind it cannot be said that anything like finality has been attained in boiler practice.

*Historical and Retrospective.*—Without some reference to the past the future would be robbed of much of its glory, because the past supplied the incentive to present practice, and will urge on future improvement.

As far back as 1686 the Marquis of Worcester operated a separate boiler, though the first actual steam boiler was the production of Lavery in 1697.

In the year 1785 James Watt added something to the boiler used in his time; but from that time until 1842 little real improvement occurred, though many, no doubt, were engaged on the problem. It was not until 1842 that the matter received earnest attention, when construction, safety, and efficiency were considered, and as a result of this revival all sorts of ideas got afloat.

It was at this time when the idea gained ground

that to prevent smoke meant saving fuel. However true or erroneous the idea, it served the purpose of forcing efficiency to the front, and it has retained its hold until the present day.

The Manchester and South Kensington Exhibitions gave a fillip to inventors who flooded the exhibitions with an endless range of apparatus—all with the intention of consuming smoke and *saving fuel.* Mr. D. K. Clark, in his official capacity of testing engineer to the "Smoke Abatement Committee," carried out numerous tests, and these included an endless variety of apparatus and methods, from which probably some useful data were obtained.

Certainly the exhibition did good; but the smoke problem was not solved—though dense volumes of smoke were often changed into less perceivable volumes, yet nevertheless the actual quantity was not reduced.

As a result of the two exhibitions the market became flooded with furnaces and apparatus. Some of these were lauded by the chemist, but many were pushed against his advice.

Marvellous cures were claimed, and as much as 50 per cent advantage was claimed; yet the smoke nuisance was not solved, and is not to-day.

It is very probable that the mitigation of the smoke was due more to the activity of municipal corporation officials than to any benefit derived from special apparatus.

The fear of punishment led boiler users to be more attentive, because many delinquents were haled before the magistrates and heavily fined, and such fines were increased in proportion to the num-

ber of times the neglectful parties were caught. Probably natural, physical, and the more mindful attention of men reduced the short time dense volume smoke, which was deemed objectionable, into the long time continuous light colour smoke, though the actual quantity remained.

It is not easy to consume smoke, and though some of the smoke-consuming appliances are, and were, probably good, the human element, when cornered, was possibly responsible for a bettered state of things, measured by light smoke occurring over a longer time than a denser smoke for a short time.

Saving 50 per cent of fuel, fifty years ago, meant much, but it would not be difficult to get a similar result from many steam-producing plants of to-day, where the probable fuel efficiency is much below 50 per cent for the fuel referred to its estimated value. Probably the saving in the past could have been effected with no other apparatus than a few stoking tools, used with some extra intelligence.

During the last twenty years much has been done to collect sound data of boiler performance, and deductions, arising out of the tests, have resulted in considerable advantage.

Unfortunately scientific experiments are conducted on lines not usual to practice, and as a result they fail to be of real advantage to boiler users; besides, as a general assertion, too many objects are sought for at one time, which frequently hamper future usefulness by referring the results to an improper cause.

Dr. Nicolson proved the possibility of multiplying the transmission rate of heat through the furnace-heating surface of a Cornish boiler; yet the

cause to which he attributed the success may not be that which really influenced the final result.

All these doubtful factors make the subject of steam boilers interesting, but complicated, and the very existence of problems goes to prove that there is some weakness in the laws relating to combustion, and until these causes which produce the abnormal results are revealed, there is need for progressive examination.

In spite of the demand for high pressures, that demand has been met, thanks to the introduction of mild high-tensile steel; but the gradual growth of pressure up to 300 lb. per square inch brought the question of weight into being which pressed heavily upon such boilers as the Scotch marine type, and this is especially true in regard to naval boilers, where light weight and sectional construction are important factors.

*Types of Boilers.*—Three general types are known, but these are again divided into many special forms. The three subdivisions are known as locomotive, marine, and stationary.

The question of the best type for naval purposes had for so long pressed heavily on those responsible, that they gladly availed themselves of the advantage of the light weight water-tube boiler—the Belleville.

Even to-day the battle of the boilers for our navy goes on, and no actual conclusion of a definite character has been arrived at, because the present adaptations are merely on their trial.

The Scotch boiler is most favoured in the mercantile marine, and is still retained on the navy list, in spite of its size and weight. Under natural

draught, working under ordinary practice, when burning 25 lb. of coal per square foot of grate, it can evaporate from 9 to 10 lb. of water from 100° F. under a steam pressure of 150 and 160 lb. with ease and safety.

The navy want 200 lb. and more, and the Scotch boiler meets the demand, but with 25 per cent greater weight than its water-tube competitor for equal power.

A comparison of the two types shows their relative fitness for the work they are called upon to perform.

*Scotch Boiler.*—It can be safely worked with salt water, and it is readily accessible for examination and repairs, or re-tubing; but heavy repairs entail a large expenditure.

They are safe, reliable, efficient, and economical, both in regard to consumption of fuel and repairs, even when compared with boilers of the water-tube type.

They are made up to 16 feet, or more diameter, and as every inch of diameter is subject to the enormous pressures now carried, an idea of the tremendous strength and weight is evident.

Two ships were placed in competition by the Admiralty, the "Minerva" which was equipped with Scotch boilers, and the "Hyacinth" with the Belleville water-tube type, and in the end little was left to choose between the two for steam supply and economy; therefore the question of weight and portability of parts only remained.

Since then the Belleville has been discarded in favour of the Babcock and Wilcox water-tube boilers; yet it is significant that four-fifths of the navy re-

quirements are supplied by the water-tube type, and one-fifth by the Scotch.

This is sufficient evidence that value is still attached to the Scotch boiler, and the real question for future consideration is whether the fire tube, or water tube, is best for the larger naval elements.

Destroyers and torpedo boats are furnished with boilers of special construction.

*Stationary Boilers.*—These include fire and water-tube types in great variety; but the one most extensively used and known is the Lancashire, or two-flued boiler, and when this is amalgamated with Galloway additions it is nearly an ideal boiler for large installations, because it is relatively safe and reliable.

In James Watt's time the wagon boiler, made up to 7 feet wide by 25 feet long, fired underneath from a large grate area, under slow combustion conditions, suited the low pressures of that period; but it was exceedingly wasteful compared with boilers of the present day.

By a gradual development the steam boiler increased in efficiency. Water pockets beneath were added, then internal flues through which the gases passed after traversing the bottom; and as pressures still increased diagonal stays were introduced; but the continual rise of pressure caused them to be displaced by the egg-ended boiler, a long, plain cylinder with rounded ends, which was termed the high-pressure boiler of its day.

Such boilers are still used in some collieries, burning colliery refuse on a large grate area, and with some success.

Their simplicity, when arranged in batteries, and fired with the waste gas from the blast furnace, are found to be convenient and suitable.

Although their small diameter seems suitable for standing a high pressure, their great length is a danger by allowing unequal stresses, due to fire contact with the under surface.

Another step led to the elephant boiler, to which many of the boilers of to-day bear a strong family likeness.

Never in the whole history of steam production were there so many boilers extant to effect the purpose intended as there are at present.

A short description of some of the boilers now in use, aided by diagrams, will serve the useful purpose of comparison and assist the end in view.

## CHAPTER V.

### VERTICAL BOILERS.

The plain vertical boiler with its cylindrical furnace and uptake through the top is self-contained; it makes steam quickly and uses fuel rapidly.

Fig. 1 shows a sectional view of the type, which needs no foundation other than that required to carry its own weight, and the small sizes are easily accommodated by any level piece of ground.

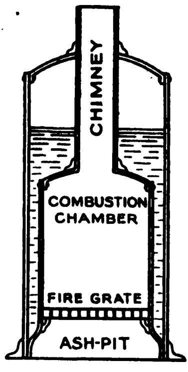


Fig. 1.—Vertical Boiler.

Their cheapness ensures their popularity; and they are useful for temporary installation for small power elements.

Unfortunately they are very inefficient, and require constant attention to keep the steam pressure steady and the water level; besides they only utilize about 50 per cent of the estimated heat value of the fuel as a maximum; about 45 per cent is more like the average, which is not unreasonable for a boiler where evaporation is due, principally, to direct or radiant heat, because most of the gaseous products are merely ejected into the atmosphere by the chimney. Numerous improvements and develop-

ments have been added to improve its efficiency, such as cross tubes above the fire, vertical tubes between the furnace crown and top, and Field tubes suspended from the crown, dipping towards the fire. All these departures from the simple type have resulted in economy.

The plain cylindrical type needs little description, because it is so well known to most steam users. It is easily made, and that has brought numerous makers into the market who have been largely assisted by makers of sectional parts as specialities, who supply crowns, angle rings, and even rolled and welded shells, leaving the mere assembling to firms who are able to quote low prices, which, under keen competition, have resulted in a poor production which has given the boiler a bad name; whereas a really good, plain vertical boiler is useful, cheap, convenient, and admirable for many purposes.

Perhaps the greatest improvement in the type is the "Cochran," with fire tubes arranged above the fire, which requires a specially made furnace tube, and the addition of a combustion chamber and smoke box at the opposite side from which the chimney springs.

This boiler is largely used on ships for hoisting and other purposes, and is usually called the "donkey boiler". It serves a useful and indispensable purpose when the main boilers are not at work.

It is a quick steamer, fairly economical, even with the small sizes, and its simple and self-contained character, with the additional advantage of being easily installed, makes it a favourite for small river

steamers and for other important though minor purposes. Its light weight for the power supplied is another advantage, and the small ground space it occupies has led to its adoption as a steam generator for considerable powers.

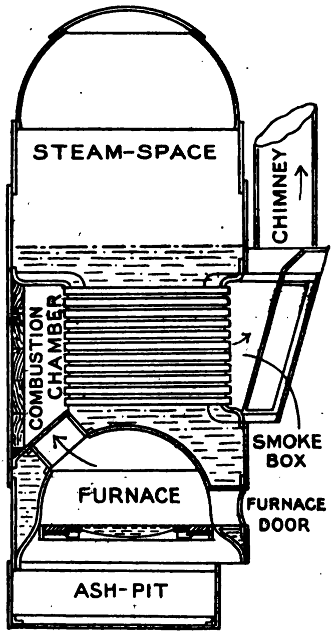



FIG. 2.—Diagram of Cochran Boiler.

Fig. 2 is a sectional elevation of a Cochran boiler, and though like other drawings in the book it is not drawn to scale, still it gives a sufficiently clear idea of what the boiler is like.

The diagram clearly shows the large heating surface and roomy steam space, whilst the low-crowned furnace allows of close contact with the

fire, and under the close action of radiant heat it is a rapid evaporator even from cold water. Its economy is due to the large number of short tubes through which the very hot gases pass, and on their way to the smoke box transmit a large part of their heat to the closely packed heating surface, and to the water in contact with it.

Obviously it partakes of the disabilities of all vertical boilers, which require close and careful attention to ensure a steady supply of steam, because the reservoir capacity is limited.

To a number of users such a boiler is ideal for their purpose, and its character precludes the possibility of inexpert manufacture, and thereby its character is saved from the bad odour from which its prototype, the plain vertical boiler, suffers.

At this stage it must be said that though the cheap vertical boilers have earned an unenviable notoriety, it is only in regard to the mushroom growths and not to the production of reliable firms. It is true that their manufacture needs no special ability; yet when made by well-known firms they serve a useful purpose and are fairly safe under careful handling. In fact they are as reliable and safe as any boiler where attention is given, and a knowledge of their peculiarities is used to save them from becoming dangerous.

The internal flued boiler of the horizontal type, such as the Cornish in its simplest form, is familiar, with its cylindrical body and one internal tube running from end to end, of which the first 6 feet is allocated to the furnace and fire-grate. Fig. 3 gives a graphic outline of its construction sectionally in front and

side elevation, which is fairly descriptive of its class. The short length shown is merely for convenience, because the actual length behind the bridge may be a total length of 14 to 20 feet; the sketch gives the general idea.

The furnace-grate is placed about midway of the diameter of the internal tube, arranged with the bars

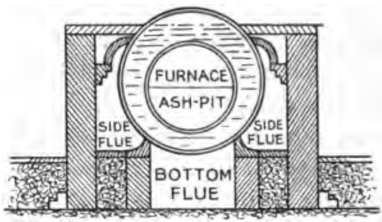



FIG. 3.—Cornish Boiler. (Front View.)

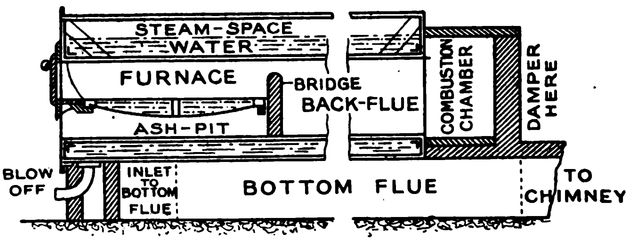



FIG. 3.—Cornish Boiler. (Side View.)

slightly slanting down at the back to where a cross wall, or, as it is termed, the bridge, completes the furnace part.

The gaseous products given off from the fire pass over the bridge to the flue behind, and expand to the larger area, and in their passage through the tube they lose heat to the surface exposed to them, which conducts the heat to the water inside. After tra-

versing the single tube the gases enter an enlarged chamber formed of brickwork beyond the end of the boiler, where a middle wall breaks the volume into two parts, one passing to the left and the other to the right; then along side passages formed by walls covered at the top, which is a little below the water level, or at it, and even sometimes slightly above it, this being a matter of arrangement, but generally the roof of the side passage is near the water level.

As one side of the wing passages is the boiler shell, heat is transmitted to the water; but considerable heat remains in the gases as they leave the wing flues, therefore the two volumes join near the front, and enter a flue built below the boiler, and usually move towards an outlet beneath and beyond the combustion chamber which is built on to the end of the boiler. During the final journey the gases lose heat to the crown of the flue, which is the curved surface of the bottom of the boiler, and the outlet is guarded by a damper which they pass before they reach the chimney.

When the first boiler of its class was introduced in 1804, it marked a distinct advance in boiler practice.

Even to-day many Cornish boilers are installed because they are safe, are easily handled, have a fairly good reservoir factor, and a fairly large steam space; besides they are much more economical than the vertical boiler, and the small amount of attention they require, due to their increased reservoir capacity, makes them a desirable steam generator to install for reasonable powers.

The boiler indicated by the sketches is about 10 feet long by 4 feet diameter, and is capable of evaporating about 800 lb. of water per hour, under an efficiency of 55 per cent with reasonable attention and care, and good fuel.

Cornish boilers have a large water capacity, though a somewhat restricted steam space, for which reason a dome is placed on the top, of some height, from which the supply of steam is drawn.

Though boilers of this class have been constructed to 7 feet diameter by 30 feet length, they all labour under the disadvantage of a small steam supply, for which, and other reasons, the Cornish has gradually but surely been replaced by the two-fluid, or Lancashire boiler; and to-day the Galloway-Lancashire boiler, with its two furnace tubes, and a large oval flue crossed with water tubes joined up to the two furnace tubes, is a favourite.

These boilers have a large water storage, a fairly good steam supply, are easily worked, and have an efficiency of about 65 per cent, of which at least 2 per cent may be credited to the Galloway improvement.

The description of the Cornish boiler, referred to the two sketches, is fairly descriptive of the Lancashire also, except for the additional tube.

A comparison is drawn between the two classes as follows, both referred to 7 feet diameter and 30 feet length :—

With a diameter of 7 feet, or an area of 38·48 square feet, the introduction of a flue tube of 7·06 square feet reduces the area to 31·42, this being the combined space for water and steam storage. Fig.

4 is a sketch of such a boiler taken on its cross section.

As quite an arbitrary determination, let the space between the bottom of the flue and the inside of the boiler shell equal 6 inches, and the water level, 8 inches over the top of the flue, and assuming the thickness of the shell is $\frac{1}{2}$ inch, and the flue $\frac{3}{8}$ for a 36 inch diameter tube, the relative dimensions are as follows:—

The length of the versed sine of the arched part of the boiler above the water level = about 32·34 inches, say $32\frac{1}{4}$ inches.

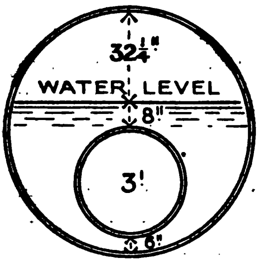


FIG. 4.

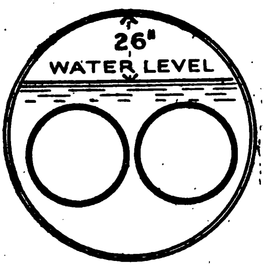


FIG. 5.

Fig. 5 is a section of the Lancashire two-flued type. In this case the flues are 33 inches diameter inside, and the thickness $\frac{3}{8}$ inch. As the water level is only 26 inches from the top of the boiler the steam space is more restricted than the Cornish boiler, but the water capacity is also greatly reduced by using two flues.

As a comparison the relative capacities of the two types are as follows, referred to the full area approximately:—

| | Cornish | Lancashire |
|---|---|---|
| Steam space . | 27·77 per cent | 20·73 per cent |
| Flue . . . | 18·36 ,, | 30·00 ,, |
| Water . . | 58·86 ,, | 49·86 ,, |

This shows the Cornish boiler to be 7 per cent better off for steam space than the Lancashire, but the Lancashire carries 4·59 per cent less water, therefore, in this direction the Cornish boiler shows to advantage; but the Lancashire boiler carries 33 square feet of grate area, compared with 18 square feet of the Cornish, or the ratio is 1·83 to 1, and both boilers can burn the same quantity of fuel per square foot of grate per furnace.

Comparing the heating surface of Lancashire to Cornish, the ratio of the heating surfaces is as 1·89 to 1; or, for level conditions, the Lancashire boiler is nearly 90 per cent superior to the other as a steam generator or quantity.

As both boilers are equal as to size, the wing and bottom flues are assumedly equal also, and as space is a valuable asset, if a boiler has a quantitative efficiency of 90 per cent over another, other things being equal, its advantages are so enormous, and its general economy so pronounced, that its popularity is warranted.

The evaporative value of a Cornish boiler, as guaranteed by a well-known firm of boiler makers, for the dimensions mentioned, equal 3120 lb. per hour, and *pro rata* for the increased advantage of the Lancashire its evaporation is 5803 lb., or as 1 to 1·86, which makes the Lancashire ·86 times better than the other.

The makers guarantee 5500 lb., therefore the pre-

vious deduction is practically substantiated; but the cause of the difference, or 303 lb., may be accounted for by reference to the known lower temperature of the waste gases from the Cornish boiler.

Let the heat value of 1 lb. of steam equal 1175·2 B.Th.U. Then multiplying this by 303 we have 356,085 units of heat which must be accounted for.

Say that 12 lb. of coal are consumed per square foot of fire-grate, in both cases for equal air supplies of say, 15 lb. per lb. of fuel, then 16 lb. of gaseous product per lb. for 396 lb. of coal burnt on 33 square feet of grate gives 6336 lb. of gaseous product.

Taking the specific heat as ·243, $\cdot 243 \times 6336 = 1539\cdot 6$ units of heat are required to raise the temperature of the products of combustion 1° F., and $356{,}085 \div 1539\cdot 6 = 231°$ F. being the assumed excess temperature of the waste gases which leave the Lancashire boiler above that of the Cornish.

Generally the calculated result is borne out in practice, because the temperature of the waste gases from a properly worked Cornish boiler are about 400° F. and for the Lancashire 650° F.

For actual fuel economy the Cornish boiler is superior to the other for equal quantities of fuel burnt on 1 square foot of grate. Practice proves that the Cornish boiler is capable of evaporating more water per lb. of fuel than the Lancashire; therefore the Cornish is the most economical.

Now, economy is relative, and it is of much greater importance to obtain nearly double the steam supply from a plant which costs very little more than another, in spite of a small advantage in fuel economy

for the less costly plant when referred to the value per boiler.

The brickwork settings for both boilers are about equal, but the evaporative advantage for the Lancashire is easily 80 per cent, whilst the fuel loss may be but a trifle; therefore a plant that costs, say, 30 per cent more than another, whilst affecting a quantitative advantage of 80 per cent, is certainly 50 per cent better as an economical factor.

The whole advantage is due to the insertion of two fire-tubes instead of one.

Large batteries of Lancashire boilers, of the Galloway type, are installed in electric light and other power stations, and universally they give satisfaction, besides being fairly economical steam producers.

The boilers named are not the only ones existent, yet they are types of the others; therefore they may be taken as fairly representative of a very large number of fire-tube steam producers made by a variety of firms in quite as many patterns, but all, more or less, conform to usual practice.

# CHAPTER VI.

## MARINE, OR SCOTCH BOILER, ETC.

THE large cylindrical boiler with its tube furnaces, combustion chamber, and return tubes above the furnaces is so familar as to need little description; whilst its retention as one of the boilers for man-of-war purposes is a proof of its utility and reliability, in spite of its huge size and enormous weight. They are made up to 17 feet diameter with three and four furnaces, joined up at the back to roomy combustion chambers, from which the gases are carried back to the front by a large number of fire-tubes whose outer ends, at the front, are accessible by the smoke-box situated at the root of the chimney up-take.

Their continued popularity is due to their safety, and consistent, steady, steam supply, besides their economy, and relative safety for almost any pressure, even up to 225 lb. per square inch, whilst supplying fairly dry steam.

Figs. 6 and 7 give front and cross-sectional views of a four-furnace boiler, double ended, with one combustion chamber common to opposite furnaces.

The diagrams are merely sketches, yet they are sufficient to convey a good idea of the class of boiler.

When worked under a moderate forced or induced

draught, they will easily burn 40 lb. of coal per

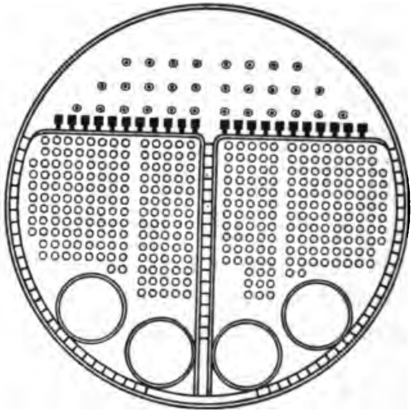


FIG. 6.—Marine or Scotch Boiler.

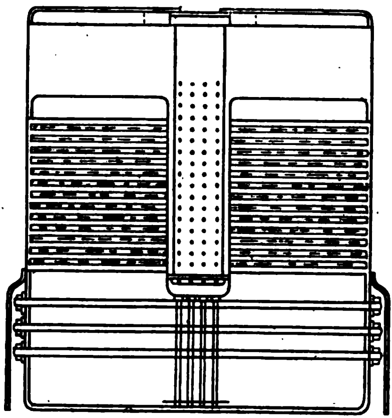


FIG. 7.—Marine or Scotch Boiler.

square foot of grate, under very reasonable economical conditions.

The boiler indicated by the sketches will burn

5760 lb. of coal on 144 square feet of grate surface, and evaporate 9 lb. of water from 32° F. to steam of the high pressure now carried, or 10 lb. of water per lb. of fuel from 100° F.

Referring such a boiler to a quadruple expansion engine using 1 lb. of coal per h.p., the horse-power value of the boiler is 5760 h.p., but increasing the draught to burn 50 per cent more fuel increases the quantitative efficiency, but a loss of 10 per cent of fuel efficiency may be expected, yet it shows that such a generator can easily meet an overload of 40 per cent, which is one of the demands for naval purposes.

Many minor additions, or rather developments, have taken place, such as corrugated flues, Serves tubes, and retarders, the latter being placed in the ends of the fire tubes at the combustion chamber end, from which an increased efficiency is obtained.

Whether such efficiency is due to the swirling action of the gases along the spiral blade, or to the frictional resistance and the check to the gas velocity, is not yet settled, though it is known that the tubes fitted with retarders show a higher efficiency whilst the gases enter the smoke box at a lower temperature with retarders, than without them.

The swirling action along the spiral course undoubtedly tends to keep the tubes cleaner, but it cannot be said to be the cause of the extra efficiency.

A very reasonable deduction which will account for the extra efficiency, is that retarders really retard the velocity of flow, and this is due to the gases being subjected to a slight compressing effect, thereby allowing a hotter gas of a denser nature to traverse

the tube in the same time, and the result is better than the ordinary condition without retarders.

Increased pressure means increased temperature and a heavier unit volume of gas. Transmission takes place in proportion to the difference between the temperature of the two faces of the tube, and under compression the difference is greater, so more heat is transmitted in the given time.

Unfortunately the use of retarders under an increased draught pressure, when burning excess quantities of fuel, gives trouble, due to excessive heating, thus causing leakage at the tube ends; therefore the suggested cause for a higher efficiency is borne out by what occurs in practice.

The Scotch boiler, when specially worked, may produce in steam 80 per cent of all the estimated fuel heat delivered to the furnace.

Messrs. John Brown & Co. of Sheffield made and tested marine boilers, which showed an efficiency of 75 per cent. The boilers were fitted with Elles and Eave's system of induced draught and Serves tubes, and the trials were made with ordinary good coal, not picked. No chimney was used; therefore, under the system with a chimney, the probability of 80 per cent being reached may be safely assumed.

An idea seems to prevail that the draught of such boilers may be forced to burn much greater quantities of fuel without losing the advantage of fuel efficiency, but this is contrary to general practice, because in most forced draught trials the efficiency fell off as the draught was increased. This and other matters will receive attention subsequently.

*Locomotive Type of Generator.*—George Stephen-

son's famous Rocket, which gained notoriety in the Rainhill trials, gave to the world the locomotive boiler; and the principles embodied in it remain to-day.

Better construction, higher pressures, larger powers, greater speeds, refinements, and developments have been obtained, yet the essential features of the old Rocket still remain, such as roomy fire-box, relatively small but long tubes, and the blast pipe,—they are still the paramount features of the locomotive boiler.

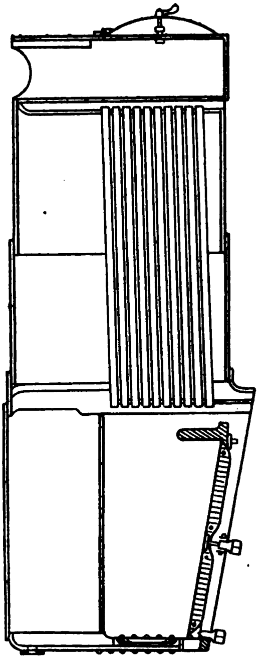
The type is used in portable engines, semi-portable, and in a modified form it is used for naval purposes for small craft.

These modifications are fairly economical for reasonable powers, but they do not compete with the locomotive in regard to output of steam, because the draught effect is not aided by the enormous forcing pressure obtained by the speed.

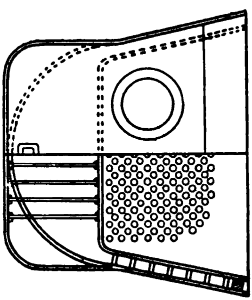
It is not too much to say that the locomotive of to-day has practically reached its limit dimensions of width and height, which are circumscribed by existing permanent way conditions, such as height of bridges, width of tunnels, and other fixed factors; but the object in view at the moment is merely to point out that the locomotive is one of many types of boilers, and not an examination of its detail.

The advantage of the locomotive boiler is its capability for burning large quantities of fuel and evaporating immense quantities of water under high pressure, and reaching a reasonable economy. It is compact and light per 1 h.p., and its suitability for high pressures, attained by the flat surfaces being

efficiently stayed without needlessly destroying accessibility for examination and repairs, are the main reasons for its introduction into the navy for limited powers.



Longitudinal Section.



Cross Section.

Fig. 8.—Locomotive Boiler.

Such a boiler is shown in Fig. 8 as made by Thornycrofts for torpedo boats. The two illustrations, though merely sketches, give a good idea of its construction and internal equipment. Much published data is available of an interesting character, such as, that by increasing the draught from 2 to 6 inches of water pressure the evaporation was increased from 6530 lb. to 10,840, but the efficiency referred to from and at 212° F. declined from 8·31 lb. to 7·03 lb. per lb. of fuel, though the weight of fuel fired was increased from 49 to 96 lb. per square foot of grate.

The expression "evaporation" from and at

212° F. is used to indicate that which would be obtained if the latent heat at 212° F. were the only amount of heat to be supplied. It is the usual standard of comparison, and is obtained by multiplying the actual evaporation by the total heat of the steam above the feed temperature and dividing by the latent heat at 212° F.

These tests merely qualify what has for a long time been understood, viz. that adding to quantitative efficiency by increasing the draught in any one boiler, generally reduces the economical efficiency under prevailing conditions. These acts present an object lesson that hustling even a boiler does not pay, and it is wise to press home the fact, because many erroneous ideas prevail in regard to what may be done with a steam boiler.

It is obvious that no comparison of this boiler with a locomotive under usual running conditions is possible, because the conditions are in no sense equal; still the type when used for torpedo generators has met with considerable success.

Modifications of the locomotive boiler have been embodied into boilers by "Galloways" where locomotive fire boxes are fitted, though it may not be fair to compare the combined type with the isolated locomotive class.

The Galloway type, fitted with a locomotive fire-box, is really an independent type combining the good qualities of two styles ingeniously amalgamated; the outside shell is cylindrical, and it may have the usual fire-box or the locomotive type. Still the oval tube exists with its cross tubes connected up to the furnace; beyond the oval tube is the com-

bustion chamber, and beyond that a nest of small tubes placed horizontally, through which the gases have to pass before dividing into the wing flues, and joining again at the entrance to the bottom flue, and back to the chimney, this being the course taken by the gases in most brick-set boilers. Such a boiler, whether fitted with locomotive fire-box or not, still presents the novel feature of Galloway water-tubes that add so much to economy. As a fact, such a boiler comprises two different elements joined together, in which one element is the ordinary Galloway and the other the multitubular, in which the water portions are in intimate connexion and the steam spaces also, the brick flues being common to both.

Many other designs of boilers bear a marked likeness to the old elephant type which is very popular abroad. One element is entirely filled with water, whilst the upper element is only partly filled, and above the two is a steam chest, termed the steam collector, from which relatively dry steam is obtained. In fact an almost endless variety of fire-tube boilers are in use and in process of construction, for which, whoever may be the maker, some special feature is claimed as an advantage.

All are intended to produce steam economically, and more or less they one and all make a very successful performance.

Amongst so many it would be impossible in a work of this size to even give each some notice, and not much advantage would be gained; but before leaving the fire-tube type there are a few matters of importance to which it is well to draw attention,

because the points are valuable, although these are equally applicable to water-tube boilers. But the sectional character of the water-tube brings in mitigating conditions which cannot be claimed for such boilers as the Scotch type, where strength is of very great importance due to the necessity of withstanding enormous aggregate pressures, for which reason the following matters are considered at this stage.

*Mild Steel.*—Mild steel enters largely into modern boiler construction and practice, and when shells of 17 feet diameter are found in marine boilers, carrying pressures of 228 lb. per square inch, aggregating a total pressure of 20 tons per inch of length, the importance of strength of material is evident.

Mild steel plates range from 26 to 42 tons tensile strength per square inch, the highest being the permissible maximum allowed for boiler shells. The carbon ranges from ·15 to ·2, the latter permitting an elongation of about 18 to 20 per cent, whilst the limit of elasticity is about half of the ultimate breaking strain.

The "Board of Trade and Lloyd's" rules generally err on the side of safety and should be adhered to. Assuming the tensile strength to be 30 tons per square inch the thickness required to stand the pressure for such a boiler is $\frac{3}{8}$ inch, and allowing a factor of safety of $4\frac{1}{2}$ it gives a plate of 1·68 inches thick; but the actual strength rests upon the riveted joints, which lower the factor. This is only given to furnish an idea of the immense weight of boilers of the Scotch type. Rules for finding the strength of the various parts of boilers can be found in many

authoritative works on boilers and their construction, and inquirers are referred to them.

The primary reason for calling attention to the strength of boiler shells is to push home the need for a close periodical examination to prevent, or check, serious oxidation, or rusting away of material which may be due to some slight leakage, or persistent dampness at some local part; because neglect may greatly endanger the strength of the plates to resist the regular pressure, or be capable of meeting some extra pressure due to some unknown cause.

Though this is particularly the province of the boiler inspectors, in all cases some responsible person associated with the plant should examine, personally, and thereby prevent ultimate damage.

All leaks should receive attention at the earliest moment both for safety and economy.

Not only does a boiler require attention during its working periods, but it needs careful consideration at other times, because boilers depreciate in value as much as 5 to 7 per cent per annum, but wear and tear can be reduced by the observation of a few very common-sense rules, whereby the life of a steam plant may be lengthened and money will be saved.

Whatever may be the rate of combustion, regularity, including systematic firing, correct and regular feeding, are all adjuncts to success and economy.

The flat ends of boilers are largely trusting to the strength of stays to withstand inside pressure, and the ends of such stays, next to the plates, are liable to become corroded; therefore, all oxidation should

be cleared away and the part painted with good paint.

The longitudinal seams in lapped plates are subjected to grooving, either due to alternate expansion and contraction, or to the scouring action of circulation, especially when dirty water is used, though a dirty boiler should never be permitted.

The general purpose in all fire-tube boilers, and indeed in all boilers, is regular and consistent applications of heat, and the avoidance of rapid changes of temperature.

But in fire-tube boilers, where the fire-grate forms part of the internal tube, it is particularly necessary to preserve as consistent a temperature as possible to avoid unequal expansions, and their attendant seriousness. Where the outer shell of a boiler and the stays and part of the ends are at a temperature of say 300° F., with the furnace-tube at probably 1500° F. at the top, and perhaps 600° F. at the bottom, erratic and uneven firing must incite a straining of both the ends of the boiler, that tends to distort the cylindrical shape of the fire-tube, and thereby reduce its strength to withstand any compressing pressure.

Leaks at any part of a boiler mean loss, be it only a few leaky cocks or a badly fitting safety valve; they all aggregate and become a serious loss on the day's performance. These matters are mentioned here because they refer to the life of a boiler, but in the proper place, when dealing with the combustion of fuel, these and other points will receive extended notice.

Standard works of reference are available to most,

but they probably do not commend themselves to the majority of men associated with the use of steam boilers. Besides, a man must be fairly well educated to be able to understand the mathematical formulæ introduced into many, for which reasons the few simple references have been made.

The demand for a class of boiler made up of a number of relatively light-weight elements was forced upon boilermakers and engineers by the requirements of colonial and foreign users, who in many cases had to install them in places far away from civilized centres, after cartage over ground that nearly precluded the conveyance of huge pieces, such as represented by those of the Lancashire or kindred types.

The naval constructors of this and other nations likewise demanded the sectional type for reasons perhaps a little hard to understand; but such reasons seemed to be of sufficient importance when backed by a determined demand to incite the introduction of the water-tube boiler.

Whether its introduction and extended use will ever entirely supersede the fire-tube is a question not yet answered, and time alone can solve the problem; therefore an extended notice must be given to a type which, to-day, is a prolific source of speculation, besides being, unquestionably, a boiler of very high efficiency and a good steam generator, however many faults it may possess. It has yet to be proved that it is superior to its fire-tube competitor, or otherwise. Anyway, it has to be reckoned with.

## CHAPTER VII.

### WATER-TUBE BOILERS.

WATER-TUBE boilers, as their name implies, have the water inside, whereas the fire-tube has it outside; but to attempt even a notice of all the water-tube boilers now exploited would be outside of the present purpose. All are intended to produce steam, and their general design allows the complete boiler to consist of a large number of comparatively light-weight elements, and they present relatively small quantities of water to be acted upon by a wide distribution of heat.

The real cause for their present popularity was the demand for high pressures for naval purposes, and though the Scotch type was able to meet the demand, the enormous weight, resulting from the greatly increased pressures, gave the water-tube its opportunity.

The water-tube boiler was in use sixty years ago, when steam pressures of 20 to 30 lb. were common; but the introduction of 60 lb. brought the water-tubes into prominent use, because the public looked upon an increase of 100 per cent of pressure as an absolutely dangerous point for the fire-tube boiler to stand.

To-day 300 lb. per square inch is common, yet the fire-tube boiler still exists, and is likely to.

With such pressures the necessity for the sectional water-tube is greater to-day than ever, not because the fire-tube cannot meet the demand of pressure, but because of the enormous weight entailed under the conditions. In regard to foreign exportation the cost of carriage of the fire-tube boiler is prohibitory, making its installation costly.

Horse-power for horse-power the water-tube is 25 per cent lighter as a complete boiler, and the heaviest section is light enough to make transport easy, whilst its installation does not demand more than ordinary lifting tackle.

The French Navy adopted the type as represented by the Belleville, and afterwards the American Navy used it in some of their man-of-war ships. But it was only after its rather extensive use by others that the British Admiralty adopted it, and so satisfied were they with a successful trial on the "Sharp-shooter" that they quickly installed the boiler in the battleships "Powerful" and "Terrible," and this was as quickly followed by its introduction into many other ships of various kinds, until it bade fair to become the standard boiler in British practice.

This was brought about by the smallness of the space occupied and the light weight per horse-power, because space and weight are valuable considerations at any time, but more especially on warships, where armour plates and heavy ordnance add so much to displacement.

Further, detailed construction assumed an importance under the idea that under war conditions the destruction of an element that could easily be replaced became a minor matter, whereas the per-

foration of a huge Scotch boiler might mean a catastrophe.

The Belleville has been so much talked about and its constructive character has so often been diagrammatically shown as to make it superfluous to indicate it here, yet some slight description may be needed to give an idea of its general principle and arrangement.

It includes a top drum, a receiver, and a feed drum at the bottom, the two being connected by a continuous length of piping nested together like a flattened spring. This piping is, relatively, of large diameter with the ends jointed into two junction boxes. The front one is provided with hand-holes and covers, opposite the end of each tube, and the top of each box is connected to the steam drum by short pipes, whose inlet ends project into the drum and are protected by baffle plates against which the steam dashes, and the water clings to the plates and runs down to the bottom. External to the boiler is a separator fitted with a spiral baffle which still further extracts the water, which is automatically carried off by a drain trap at the bottom ; therefore the steam is delivered to the engines relatively dry, which is of considerable advantage, because it lessens cylinder condensation.

Independent circulating pipes, apparatus to prevent priming, feed arrangements, and a reducing pressure valve, are provided.

The efficiency of the boiler is good, but where so many separate parts are jointed together they are so many points for leakage, and in practice the aggregate leakage is considerable. The construction is expensive, because so much fitting is needed. In

spite of the most careful attention leakage is hard to prevent, making the Belleville a very wet boiler, which detracts from its efficiency.

Its water capacity is exceedingly limited, calling for a constant feed; besides, nothing but condensed water can be used, and this means the need of a condensing plant.

The boiler has many advantages, but they are overbalanced by its disadvantages, and for the latter reason, after careful expert deliberation, the Committee appointed under Parliament have condemned its further use for the British Navy.

Amongst the many water-tube boilers suggested to take its place, the Babcock and Wilcox was selected, and since then many of that make have been installed, and are favourably reported upon.

Apparently they are giving satisfaction, because they are included in the four-fifths of the Navy requirements. That was the published determination, and unless some unforeseen disability arises the Babcock and Wilcox may become the service boiler for the Admiralty, in spite of the fact that their requirements are difficult to meet.

The Admiralty demand, for the consumption of 18 lb. of coal per square foot of grate, 12 lb. of water evaporated from and at 212° F. For 24 lb. $11\frac{1}{2}$ lb. of water, and 30 lb. 11 lb. of water for equal conditions.

Thus far the Babcock and Wilcox boiler has met the conditions in every point.

The navy pattern is slightly different from the usual Babcock and Wilcox's type; the difference is that the steam drum is placed in a line with the furnace

doors provided with the necessary fittings, as in the usual type.

Fig. 9 is a sectional view which gives an idea of the general arrangement.

The front header is made of mild steel, and occupies a position beneath the steam drum, and is

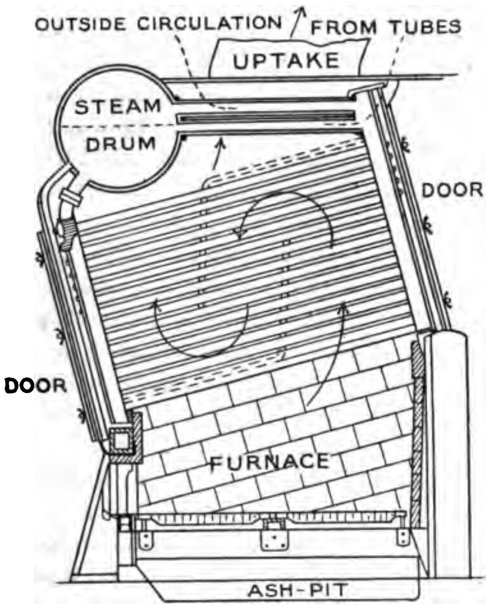



FIG. 9.—Babcock and Wilcox Marine Type Boiler.

connected up to it with short pipes; the header is placed at an angle with its lower end inclined towards the centre of the boiler, and parallel to the back header whose lower end rests upon, or rather abuts upon, the back wall of the furnace chamber. Between the two headers are straight tubes arranged

in staggered order, each end being expanded into the adjacent header-hole prepared to receive it, and each end is accessible by a hand-hole—provided with a cover, dog, stud, and nut—similar to the ordinary mud-hole doors of the fire-tube boiler.

The back header is connected up to the steam drum by horizontal pipes which enter the drum above the water level, which is generally half full of water.

Besides these connexions two others are made with the headers, one beneath the water for the front header, and the other above the back header connexion, which arrangement ensures a definite circulation in one direction.

The furnaces enclose all the tubes, and by a system of baffle plates the gases and flame are compelled to take a sinuous course from the back to the front of the tubes before entering the uptake, and the delivery tubes from the back header are subjected to the escaping heat thus, ensuring a dry steam discharge above the water.

The heating surface is large, and as there are no flat surfaces to strengthen it is a safe construction.

Compared with the Belleville the Babcock and Wilcox boiler can be cheaply made, but clean water is essential.

Generally, the boiler is simple, efficient, and easily accessible. A split tube, when located, is easily replaced, but it is very difficult to locate the position of a leaky tube amongst so many, when compared with locating a split tube in a fire-tube boiler, in which the leakage shows inside the tube and out at the end.

Whilst the Babcock and Wilcox has received so much prominence it does not mean that other types are not worthy of attention; but suitability in regard to space, for power, gives the opportunity which the makers have taken.

Eminent firms of boiler makers are not lacking in enterprise or in ingenuity, and Galloway's Limited have met the case for high pressures by the introduction of the Manchester water-tube boiler to take the place of the Galloway-Lancashire, where sectional parts are an advantage and high pressure a necessity.

In some respects it is like the Babcock and Wilcox, though primarily it is intended for land service alone.

The long experience of the firm and their unquestioned ability may result in their producing a design suitable for naval purposes, and their name will go a long way in establishing confidence in any generator they may put upon the market.

Other boilers made by equally reliable firms, might be referred to, but want of space prevents their description; besides, the issue is with generators that have obtained some special notoriety, such as the Normand for naval purposes.

*Normand.*—This is a boiler where one large drum is placed centrally over the furnace in a line with it, flanked by two smaller drums at the bottom, one at each side of the furnace. The three are connected up to quite a battery of small tubes lying close together, and shaped to form an arch over the fire with the extreme ends attached to the three drums. Large tubes join up the three ends of the drums to ensure circulation.

One of the chief claims for this boiler is the small amount of brickwork needed, due to the closeness of the tubes, that present nearly a solid wall. It labours under the disadvantage common to all members of its class, namely that no mechanical method can be used to keep the outside of the tubes free from sooty deposit.

The British Navy have some in use with up to as much as 8000 square feet of heating surface, for 154 square feet of grate area; whilst the consumption is about 1·36 lb. of coal per indicated horse-power. All the evaporating tubes deliver into the water, and it is just here where so many divergencies occur, because some deliver below the water, others at the surface, and the rest above. The Thornycroft differs from the Normand in this respect, also in the shape given to the tubes. They all deliver above the water level, even into the very top of the top drum, and they lie close together. What is called the Thornycroft Speedy type is shown in Fig. 10.

The objections to this boiler are similar to the Normand, because the outsides of the tubes cannot be mechanically kept free from soot.

The advantage claimed by the Normand in regard to the small amount of brickwork required can be claimed for the Speedy type, because the closeness of the tubes enables a casing to be used instead of brickwork.

Another class of boiler is made by Thornycroft, called the Daring type. It has only one upper and one lower drum, joined together by a number of small tubes bent to the shape of a heart. The inside layer of tubes enters the drum below the water

level, and the rest discharge into the steam space. At one end the drums project beyond the general face, and a large pipe connects them, the other ends being joined by smaller tubes. The shape given to the tubes makes two furnaces necessary, but a much larger surface is exposed as heating surface. One point is noticeable in that the upper drum and all the tubes are completely enveloped in heat, whilst the lower drum and the connexions to it are completely protected from contact with the fires.

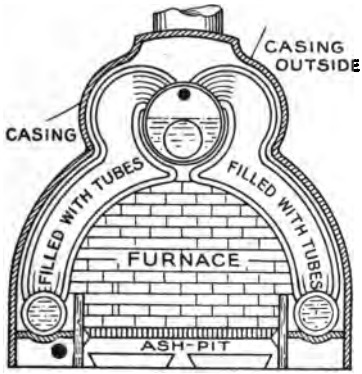



Fig. 10.—Thornycroft Speedy Type Boiler.

All boilers of this class are efficient evaporators, and are fairly economical of fuel, but they all are objected to as inaccessible for repairs and cleaning.

The roomy furnaces and the direct action of radiant heat upon sections of the tubes make circulation certain, aided by the other methods adopted, thus ensuring a continuous movement of the water from the coldest to the hottest points, and the reverse.

So far none are used for very large powers, in spite of their efficiency.

The figure below makes the general arrangement clear, and it needs no further description.

*Fleming and Ferguson* make a similar class of boiler, but the tubes are bowed from the lower drums to the upper.

*Seaton's* boiler differs from all of this type as the large drum is one of five, and is placed in the centre with two above and two below. The five are joined

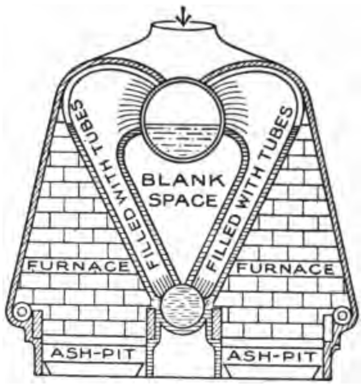



Fig. 11.—Thornycroft Boiler.

together star fashion by straight tubes, but the upper and lower drums are connected by bent tubes.

Whatever the particular configuration, they alike have advantages and disadvantages.

One other boiler may be referred to in this connexion, but it possesses special features, namely the

Neclausse.—It may be summed up in saying that apparently its sectional character has been carried beyond reasonable limits, and though highly efficient, it is much too complicated for naval purposes.

*Yarrow Boiler.*—This is one of the best boilers

that practice has demonstrated for efficiency, rapidity of evaporation, dryness of steam, and economy.

It is comparable with the Normand and Thornycroft in their best features, but it differs in two essential particulars.

Its three drums are arranged as in the Speedy type, but the connecting tubes are all straight, and as each bottom drum is fitted with a removable cover, into which the bottom ends of the tubes are expanded, the chief difficulty of want of accessibility is removed; besides mechanical means can be applied to keep the tubes free from sooty deposit because they are straight. All the tubes enter the top drum well below the water level, and only one large fire-grate is used. The bottom covers of the lower drums are connected up by flanges and bolts and nuts; whilst both drums and covers, also the ends of the tubes, are efficiently protected from direct heat. After the gases pass through the stack of tubes they envelop the top drum, and this gives a dry steam supply.

All the good features of the type have been conserved, and every disability has been swept away.

This is one of the boilers recommended by the Parliamentary Committee for further trial—as a larger element—for warships of the larger class.

Of course the tubes and drums will be made in proportion to the demand for power; but essentially the smaller type will furnish the principle.

*Stirling Boiler.*—This has three drums above and one large one below, and all are joined by long tubes bent at the end to enable them to nest together on the main bottom drum.

Its simplicity is evident; the tubes are of large

size and nearly straight, but for their ends, and these are made in long sweeping curves. It is essentially a land boiler, and requires much brickwork to enclose it. Its success on land has got it introduced into marine practice; but it is hardly likely to become popular as a marine generator owing to the large amount of brickwork required.

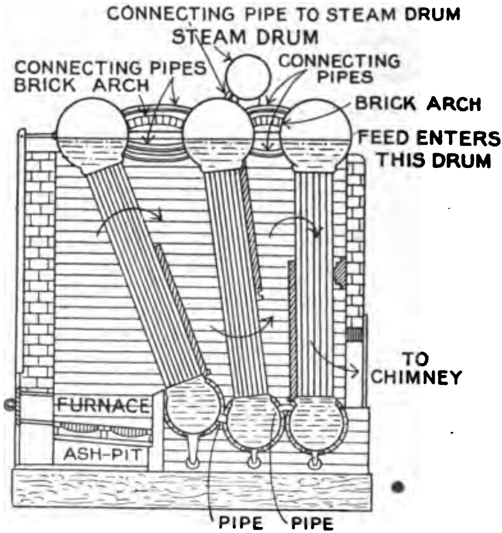



Fig. 12.—Woodeson Boiler.

One other boiler demands attention, and it may find success and popularity, because, like the Yarrow, it embodies all the good points of its competitors, and has avoided all their serious faults, or most.

Fig. 12 gives a clear idea of its general arrangement.

The *Woodeson Straight Tube Boiler.*—This boiler is made by Messrs. Clark, Chapman & Co., and

comprises three upper and three lower drums connected together in pairs, in sequence, 1, 2, 3, by large tubes of great length and perfectly straight. The ends are expanded into holes made in flat discs formed in the body of the material of the drums by hydraulic pressure, and these face each other for each pair of drums; besides all are very little out of the vertical.

The upper or steam drums are 4 feet diameter, and above each flat disc formation which groups nineteen tubes there is a manhole, enabling each tube in the group of nineteen to be got at for caulking, expanding, cleaning, or renewal.

These manholes are fitted with pressed steel covers, recessed to take an asbestos ring, and any ordinary fireman can take one off and replace it without the least fear of leaving a leaky joint.

The nearly vertical position of the tubes is a preventative against deposit from sediment on the inside, or soot outside.

The lower, or water drums, are 33 inches diameter, with a manhole at one end which gives access to all the tube ends in that drum.

Circulating pipes join up the three bottom drums, and the same occurs with the top drums, both for water level and steam space.

Feed water is admitted at the back part of the third top drum, this being the coldest part of the system. From there it flows down the rear tubes, where it is met by the lowest temperature gases; thus precipitation takes place in the lower water drum.

The front set of tubes are attacked directly by

radiant heat, and at a little above half the height of these tubes the gases and flame are diverted by a baffle plate and pass downward through the lower half of the second section, then up again through the upper half of the third section.

Brick arches span the gap between the upper drums, and these are placed between the water and steam connexions to each drum; thus the whole of the active part of the boiler is flooded with heat, and all heating surface is brought under its influence before it can escape up the uptake.

The lower drums are efficiently protected from direct fire heat, and suitable doors, placed in the side walls, give ready access for examination and repairs.

An important feature is that the construction provides against the effect of unequal expansions, because the top drums are carried on girders, supported by columns outside of the walls; the whole boiler can thus expand downwards, because the bottom drums are kept clear of the ground.

A superheater is arranged to hang down between two sets of tubes, right in the path of heat, and by-pass valves allow any degree of superheat to be obtained to suit conditions.

Some advantages are apparent, and these are important, which fig. 12 will make evident. In the horizontal water-tube boiler with a door at each end, for 342 tubes 684 doors must be removed, and the same number of joints must be remade; whereas in the Woodeson with 3000 square feet of heating surface only six manholes need be removed to get at every tube end in the boiler.

The grate area for the large boiler equals 75 square feet for 4330 square feet of heating surface, and is capable of evaporating 17,320 lb. of water under 160 lb. pressure.

But space is important in all boiler installations, and the 554 horse-power Woodeson boilers 22 feet high, 15·9 feet wide, 19·6 feet deep, giving a space of 6842 cubic feet.

They require a large amount of brickwork, about 7150 firebricks and 22,000 ordinary, and the total shipping weight is 45 tons.

Their large size is against their use for naval purposes, but a special boiler is made for this purpose.

This boiler appears to be the most serious competitor to the Yarrow for naval purposes, if it is designed to meet the necessary conditions.

As a matter of some interest, we quote the following results of some tests made in 1907 on six of these boilers as installed in the Electric Light Station, Naples.

The test was for 6·55 hours for boilers, and the following particulars are furnished by the makers :—

| | |
|---|---|
| Grate area | 59·5 sq. ft. |
| Heating surface | 3430 sq. ft. |
| Ratio | 1 to 58 |
| Gauge pressure, boilers | 185 lb. per sq. in. |
| Temperature of feed | 64° F. |
| „ of superheat | 579° F. |
| Flue temperature | 392° F. |
| „ gas $CO_2$ | 14 per cent |
| Water evaporated | 83,000 lb. |
| Coal burnt | 9876 lb. |
| lb. of water per lb. of coal | 8·4 lb. |

| | |
|---|---|
| From and at 212° F. . . . | 10·72 lb. |
| Evaporation per lb. of combustible at 212° F = 11·74 lb. | |
| Coal per sq. ft. . . . . . | 25 lb. |
| Firing, underfed stokers | |
| Estimated heat value of fuel . | 13,950 B.Th.U. |
| Efficiency . . . . . . | 80·1 per cent. |

Another test was made by Messrs. Merz & McClellan, Engineers at Newcastle-on-Tyne, in 1908, as follows:—

| | |
|---|---|
| Duration of test . . . . . | 6 hours. |
| Heating surface . . . . | 4125 sq. ft. |
| Grate area . . . . . | 90 sq. ft. |
| Ratio . . . . . . . | 1 to 43·6 |
| Gauge pressure . . . . | 180 lb. per sq. in. |
| Temperature of feed . . . | 90·4° F. |
| Superheat . . . . . | 533° F. |
| Flue temperature . . . | 515° F. |
| Draught . . . . . . | 0·75 in. |
| Flue gas $CO_2$ . . . . | 11·5 per cent |
| Water evaporated . . . | 25,500 lb. per hr. |
| Coal per hour . . . . | 2931 lb. |
| Water per lb. of coal . . . | 8·964 lb. |
| Coals per sq. ft. of grate . . | 32·5 lb. |
| Firing, chaingrate mechanical stokers . . . . . | |
| Estimated heat value of fuel . | 11,000 B.Th.U. |
| Efficiency . . . . . . | 78·3 per cent. |

This plant was installed to evaporate 18,000 lb. per hour; after the above test another was carried out without clearing the fire for a run of three hours, when an evaporation of 26,000 lb. of water per hour was obtained.

These examples are merely to show the efficiency obtained, but some water-tube boiler tests show an apparent efficiency of 90 per cent, though these can only be viewed as phenomenal performances carried out under special and ideal conditions.

## CHAPTER VIII.

### STEAM-BOILER PRACTICE.

Burning fuel in a steam-boiler furnace, by the process of combustion, and the evaporation of water for the supply of steam are so associated, that it is useless to speak of one without the other, and economy is the key-note of the combined performance; meaning that economy is greatest when the least amount of fuel will evaporate the greatest quantity of water in the generator that costs the least, and occupies the smallest space.

Burning fuel and evaporating water to the best advantage is the purpose of every boiler maker, or boiler user; but in spite of an endless variety of boilers fitted with ingenious apparatus, intended to produce an ideal result, the very best that can be credited to actual everyday performance of the engine is 1 h.p. per 1 lb. of coal of average quality per hour. Taking the estimated heat value of average good coal as 14,700 B.Th.U. per lb., and 1 h.p. equal 42 units per minute equal to a ratio of 350 to 1, therefore there is cause to look closely into the reasons why much waste so occurs.

But the case is worse than this, because a fair average for all boiler plants now in use, shows that probably an efficiency of 50 per cent is scarcely reached, and of this only about 34 is usefully

applied to steam production, the remaining 16 being carried off by the waste gases and by the other sources of heat loss.

It is seen that 34 per cent of 14,700 B.Th.U. = 4998, and, as stated a few lines back, the ratio of 42 to 14,700, is 1 to 350. Now the best efficiency is only 17 per cent, or equivalent to 2499 B.Th.U. for engine and boiler performance combined per hour.

But the present intention is not to include the engine, either in regard to any disability attached to it or its efficiency; though it is wise to present the worst phase because, probably, the boiler in some way is responsible for the low efficiency of the engine, even when the boiler shows an efficiency of 80 per cent of all the fuel burnt in the furnace.

This fact is well understood by boiler designers and experts, who adopt as many means as possible to save waste of heat at the chimney end of the boiler, and to save as much as possible at the furnace end; besides endeavouring to supply steam as dry as possible. Unfortunately, too often the attempts are but feeble, used with a desire to mitigate faults instead of getting rid of them.

The prolific source of making wet steam is the forcing a boiler to produce more than it was ever intended for.

Thus it is evident that the designer and constructor are not always at fault, and generally they are capable of producing a boiler to evaporate a given quantity of water in a set time from a determined amount of fuel. Very often the manufacturer, to ensure a sale, will force an element to an inordinate production to prove quantitative efficiency, and such

forcing necessarily increases the waste and lowers actual efficiency by increasing the chimney temperature.

The buyer is probably as culpable as the seller, because he purchases a low-priced plant with a full knowledge of its usual capacity, and after installation forces evaporation to a point that a larger plant would easily reach under fairly economical conditions and with practically no disability.

These facts are common knowledge, but however reprehensible they may be they do not enter into the present object, the main point of which is to produce a boiler with ample heating surface, and to use it to the best advantage.

Such heating surface may be placed to obtain the highest efficiency, but the intention may be foiled by adopting a method of burning fuel that is inimical to a good result, and the bad result may be made worse by a bad system of circulation, which can easily destroy the advantages of a properly placed heating surface.

*Combustion.*—This is the primary object, therefore the methods by which best results may be obtained requires consideration and careful examination.

It is scarcely necessary to assert that the best designed boiler may evaporate badly in incapable hands, whilst many a poorly designed boiler makes a good performance in capable hands.

A boiler may be flooded with heat, yet give a poor result, because it is little use pouring heat into stagnant water which transmits slowly, even as it is trying to force heat through a grease-covered

surface to the relatively cold water on the other side, and both are wilful waste of heat energy.

On the other hand it is no use forcing a fire to produce steam if the transmitting surface is covered with soot on one side, and a nearly impermeable scale on the other.

Therefore, as already referred to, cleanliness, a good circulation, and pure water, are the starting conditions to be observed, even in boilers of the best design.

The need for economy is so well understood that contrivances of every character are introduced to get a slightly higher efficiency.

One of the most up-to-date additions to steam boilers is live-steam feed, and many advantages are claimed for it, apparently justified by the effect; but where the claims refer to increased evaporative efficiency, due directly to the introduction of the live-steam feed, it requires more than a little qualification.

The way in which live-steam-feed must affect circulation seems to point to the weak spot of the system, because the advantage of one temperature in equalizing stresses in material is evident; but an equal temperature destroys natural circulation, and unless a forced circulation is provided, the condition of body-hot water at rest is opposed to rapid evaporation.

*Live-Steam Feed.*—The system may be said to include the thermal storage system, which supplies the generator with water, practically at steam heat, and the feed is gravitated into the generator.

The arrangement appears to be opposed to the

conditions required in natural circulation, except for the slight displacement caused by the entrance of the feed under a slight head; but this objection to the thermal storage is removed when forced circulation is adopted, both in the storage reservoir and in the generator.

But the claim often made "that live-steam feed results in an enormous economy," and not only made but upheld by users as a fact, requires a close examination of the principles involved in the assumed advantage.

Now, 1 lb. of steam, be it at atmospheric pressure or 300 lb. per square inch, it possesses a definite number of heat units, and the higher the pressure the greater the number; therefore live-steam feed, whatever its heat, requires fuel heat to supply it, and 1 lb. of steam cannot give to the water more heat than 1 lb. of steam holds.

The purpose of all water evaporation is the production of steam, in which is included a given quantity of latent heat; therefore total heat, including the latent heat introduced by 1 lb. of live steam, is capable of raising the temperature of so many pounds of water to its own temperature, i.e. temperature of steam. It is quite obvious that the latent heat, introduced by the 1 lb. of steam, was obtained from the fuel heat; therefore the fuel is equally capable of supplying latent heat to 1 lb. of water evaporated, without the aid of live-steam feed.

If any real economy is attained by the use of live-steam feed it must be something contingent to its use, because under no known conditions can it give

away more heat than it has received, and the fuel used must provide the heat.

Continuous feed, steady firing, and a constant water level with clean water, and with a clean boiler, are all prime factors in economy.

The vapour given off water is impregnated with fine particles of water, or the steam is said to be saturated.

*Superheated Steam.*—When saturated steam is isolated from the water of its formation, and subjected to a higher temperature, it becomes gasified or superheated, and advantage is taken of this change to get a more useful substance for use in the steam engine, as has already been referred to.

Such knowledge is not of recent growth, because it was both known and used in the earlier days of steamship practice to some advantage. Its disuse was mainly due to the injurious effect of superheat on the material, but since then materials have been improved and lubricants introduced that will remain a lubricant even at high temperatures.

It may be supposed that saturated steam is diluted by finely divided particles of water that hold much latent heat, which is available to add additional heat in making saturated steam into a gaseous substance, because the saturated steam holding highly heated water containing so much latent heat is merely awaiting a slightly additional heat to make it into a gas. It may be safely assumed that Dr. Siemens' deduction is right when he asserts that from 10° to 20° F., added to saturated steam at 212° F., marks the limit point between a non-gaseous substance and a gaseous. This supposed

latent heat storage—added to the fact that during the addition of 20° F. the substance expands five times as fast as air—appears to bear out Dr. Siemens' assertion.

The matter is too important to be lightly dismissed, if only for the reason that making saturated steam into a gas reduces condensation to a minimum, though it is not supposed for a moment that condensation can entirely be avoided; but it is conceivable to think that part of the heat applied to saturated steam to superheat it, beyond what is necessary to change it into a gas, destroys the tendency to excessive condensation by heating up the surfaces in contact with steam with the surplus heat beyond that which gasifying requires. In this connexion the plan of jacketing steam engine cylinders seems to be right, though the advantage is questioned by many even to-day.

The proof is largely one for experiment, because calculation can take no account of contingent effects that interfere with the purity of action in regard to gasified steam itself.

The early experimenters with superheated steam measured the advantage lavishly, and the results attained from some of the Peninsular and Oriental steamships savoured of the marvellous; but it is explainable by the low pressures used, and where the addition of 20° F. increased the volume five times that which would occur if the same heat was applied to the same weight of air, an enormous advantage would be gained, with a low pressure and a correspondingly low temperature.

Steam of 35 lb. absolute pressure has a temperature

of 259·3° F., latent heat 931·6, and total heat 1160·5, and a volume of 11·65 cubic feet per lb. of steam. By increasing the temperature 20° F. the volume is reduced to 8·48 under an increased pressure, and assuming superheating by adding 20° F. increases the volume, the new volume becomes 14·61 cubic feet, or where 11·65 cubic feet of steam did so much work, then 14·61 would do 28 per cent more. Now, 1 lb. of saturated steam involved 1160·5 units of heat for a temperature of 259·3° F., and 20° F. added = 7·7 per cent, and 7·7 per cent of 1160·5 = 89·3; or 28 per cent more work was done by the use of 7·7 per cent more temperature.

The deduction assumes no more than that where the cases are proportionate to one another, the rough estimation is as given.

Even allowing that, to get 20° F. of additional heat, 40° B.Th.U. per lb. had to be used, the advantage is still 28 per cent as against 15·4 per cent, or 12·6 per cent to the good. The only purpose intended is to show that superheating is an advantage under any circumstances.

The laws referring to heat effects allow that pressure increments due to adding heat follows the same ratio as that of increase of volume; therefore adding heat under a constant pressure increases the volume to the same extent as the pressure would increase if allowed to by confining the volume.

Roughly taking the pressures as 35 and 49, the ratios are as 72 and 100, or a difference of 28 per cent; therefore the contention is substantiated.

The deduction is merely a practicable one, and is not intended as an example of a method for finding

such values, but it is based on Dr. Siemens' assertion that 18° to 20° F. will change saturated steam into a gas, and referred to that rate 20° F. addition makes it appear that adding 1° F. to saturated steam, separated from the water of its evolution, requires ·626 units to produce one ordinary expansion, because the assumed expansion of saturated steam = 3·134 ÷ 5 = ·6266 units, as an average for the 20° F. addition. But it will be more for the first 1° F. added and less for the last of the 20° F., and as the last degree produces an assumed perfect gas which incorporates ·48 units for every 1° F. added, then the difference between 1 unit and ·48 = ·52 and ·52 ÷ 20 = ·026 units of heat, as specific heat, which gives the average reduction of heat required as each extra 1° F. is added. For each stage the expansion volume value is in proportion to the absolute temperature, or 1 – ·026 = ·974, meaning that for the first degree of temperature added to saturated steam ·974 units are required to produce both temperature and expansion, and for each succeeding degree added the heat required is ·026 units less, until the standard or limit of ·48 units per degree is reached. This is a reasonable deduction, as the final unit heat value, assumedly, is all taken up in adding to the temperature, because the latent heat does not increase for the reason that vaporization is perfect, and all the latent heat required has been incorporated, because all water has been evaporated and gasified.

Thus it is evident that adding heat to saturated steam after it has been gasified by increasing its temperature 20° F. must be economical, because its volume is increased by the utilization of a lower heat value which appears to be reasonable.

The deduction of a higher specific heat than that usually credited to saturated steam is borne out by its reasonableness, because a gas has a lower specific heat than water; and the nearer steam is to water the higher must its specific heat be.

When superheating saturated steam, removed from the water of its formation, it is often found in practice that to get a certain superheat twice that amount of heat must be spent.

If superheating is carried out as a separate operation apart from the boiler, whatever the advantage, it is much less than that obtained when superheating is effected within the required heat zone of a boiler flue; therefore all methods of superheating are not equally economical.

The real advantage of using superheated steam has not been grasped by the steam users of the world at large, and this need occasion no surprise, because there is nothing like unanimity of opinion even amongst experts. Indeed the opinions are so diverse, and their views so opposite, that only one conclusion can be arrived at, and that is superheat, like many other matters connected with the use of steam plants, presents a mystery which only close examination and exhaustive tests can unravel.

Whatever diversity of opinion exists on these matters, there is none in regard to the advantage of working steam plants by brainy men, including intelligent stokers. These can be obtained if the price is paid, but such price is supposed to be prohibitory; for which reason mechanical aids have been introduced, yet even these require skilled operators if the best economy is to be obtained, because, whatever

the excellence of mechanical methods may be, none have been produced that can compare with the best hand firing, both for fuel economy and quantitative efficiency.

*Production of Steam.*—Some knowledge of how steam is evolved is necessary, if only to teach what to observe and what to avoid. A simple experiment will reveal more than any amount of writing, and all the apparatus required is a common gauge glass, plugged at one end and filled with water, and placed in an angular position of say 45 to 60 degrees. The angle is not material so long as the tube is inclined considerably.

When the pointed flame of a candle is brought into contact with the underside of the tube a bubble is formed within the tube which starts upward with incredible speed to contact with the top of the tube, but the bubbles soon enlarge, until the tube is filled with them, and unless the flame is removed the glass will crack, thus showing that the heat is not conducted away fast enough. When the flame is removed the bubbles will flatten themselves against the upper surface, and gradually slide upward.

By careful manipulation of the flame a series of small bubbles will form and fly up vertically to the top, and in a flattened condition will move upwards.

This simple experiment shows what takes place inside of a steam boiler, besides teaching the lesson that perfect freedom should be given the bubbles to get away from the surface they are in contact with, otherwise serious damage may occur to the surface.

In the fire-tube boiler, in the lower part of the circular furnace such bubbles may form and cover the

surface, and if obstructed or restrained to their position they will enlarge and denude that part of water. The same thing occurs to the underside of all tubes, such as the small tubes common to the Scotch and locomotive boilers.

Wherever the vapour bubble films are retained in contact with a hot surface it is inefficient, and in practice only two-thirds of all horizontally placed, circular forms are deemed efficient, and unless care is taken to prevent the retention of the films at one place disastrous results may occur.

In a boiler with active circulation the films are quickly moved, and the so-called inefficient surfaces may be saved 50 per cent of their inefficiency.

In the relatively small tubes of the water-tube boiler pocketing occurs when circulation is laggard, and for such reasons a constant feed is necessary which acts to force circulation.

Whether in fire or water-tube boilers constant and active circulation is necessary, and for this reason the sides of the locomotive fire-box should have a decided taper inwards from the top towards the fire.

One of the chief failings of the original water-tube boiler was a congested outlet from the tube ends to the steam space in the upper drum; but in the up-to-date boiler this evil has been corrected. Still, it always pays to have sufficient freedom in the junction boxes to allow free movement of discharge from all the tube ends.

Even when all these various points have been attended to the final result rests upon combustion, and burning fuel gives rise to many complications due to the possible combination of so many gases,

that man's ingenuity is stretched to the uttermost to meet the complex demands.

Engineers, boiler experts, scientists, and chemists have battled with the problem of combustion to a useful end, yet, to-day, it bristles with difficulties, and the air we breathe is still fouled by obnoxious vapours.

The enormous disparity between the estimated heat value of a fuel, and the power obtained from the engine, has too often been saddled on engine inefficiency which is unreasonable and untrue.

Where a boiler has an efficiency of 80 per cent, not more than 20 per cent of this may be utilizable in the engine, and there is loss of heat in the passage from the boiler to the engine, and roughly, two-thirds of all the heat referred to the furnace is lost; but it is even worse than this because less than 3000 B.Th.U. per lb. of coal may reach the engine, and some of that is lost to radiation and exhaust. This has already been referred to, but it is worth repeating, because every little saving of heat is an advantage to economy. To extend the reference it is quite possible to lose 38 per cent of the assumed 3000 B.Th.U.'s. Of this only about 720 B.Th.U.'s are available for doing useful work, or less than 5 per cent of the estimated heat value of the fuel.

The engine for best conditions changes this average 5 per cent into 17 per cent, therefore the steam engine can be made much more efficient than it generally is.

The latent heat is necessary to steam formation, and its actual presence is easily demonstrated if 1 lb. of steam is mixed with 5½ lb. of water; the increased temperature of the water, where the mixing is done

under atmospheric pressure, will prove the presence of latent heat which has been transferred to sensible temperature.

With our present appliances and knowledge it is impossible to utilize latent heat, except by increasing the steam pressure to an enormous extent, and we know of no material that could stand it and also be suitable for practical manufacture.

The following aims should be considered in connexion with all steam plants:—

To get the greatest value of power from the least weight of fuel.

To get the most heat into the least quantity of water.

To obtain the most power from the least weight of steam.

To get the greatest economy from the plant costing the least money.

## CHAPTER IX.

### COMBUSTION.

SCIENTISTS and chemists, by their experiments, have provided rules and furnished values in regard to the heat value of combustibles, even in regard to their separate elements, and based upon such deductions any good technical work will furnish reliable data which may be accepted as the foundation on which all combustion problems may be based.

Although the elemental character and the heat effect on gases are widely known, yet they are of little practical use in steam boiler practice, which involves all sorts of combinations under conditions never found in the laboratory; therefore the subject of combustion bristles with difficulties, leaving much that is doubtful to be found out in the very common operation of burning fuel in a steam boiler furnace.

Sixty years ago the question of combustion was attacked with vigour, and arising out of it many experiments were made, from which a variety of deductions were drawn, resulting in quite a flood of contrivances from which much was expected but little was obtained.

Theories were discussed in rival camps, but the views were so opposite as to prevent any useful outcome from what might have been a practical solution of a difficult question.

As a broad statement of fact the most up-to-date efficiency derived from 1 lb. of coal of an estimated heat value of 14,700 B.Th.U. is 17 per cent. For these 14,700 B.Th.U. which give 14,700. × 778 = 11,348,400 foot-pounds of available energy, only 33,000 foot-pounds × 60 = 1,980,000 (i.e. 1 h.p. per hour), and as 11,348,000 : 1,980,000 : : 100 : 17, i.e., the efficiency is 17 per cent.

Generally, about 5 per cent efficiency is an average if all steam plants are taken into account.

Therefore the causes are worth investigating, if only to try and raise the efficiency 1 per cent, which is equivalent to 20 per cent actual gain on present average practice referred to the heat utilized.

Before this can be done it is necessary to know something of the estimated heat value of the fuel, and the constituents from which the heat is obtained.

Generally, coal is said to be of a composite character, in which the main elements of combustion are carbon and hydrogen.

Unfortunately these two combine in various proportions to form hydro-carbons whose chemical properties differ very materially, in spite of the fact that the constituent gases are derived from the same source.

In no sense is it intended to do more than make the conditions understandable to the lay mind; therefore anything in the nature of unnecessary complexity will be avoided, and simple terms will be used to meet the convenience of those who are not cognisant of scientific language, or calculation.

In the boiler furnace, combustion is a means of decomposing the elements, and the next purpose is

to facilitate their admixture with oxygen which forms one of the elements of the air supply; and the final object is to obtain the greatest heat value with the least loss.

*Carbon* by weight represents about 80 per cent of the total weight of 1 lb. of coal, the remaining 20 per cent being nearly all hydrogen.

Generally, it may be said that of all the atmospheric air entering the furnace, whatever the value of its oxygen element, about 84 per cent of such associates with carbon.

As a fact it may be said that $H_2O$ can be formed in half the time it takes for carbon to be converted with carbonic acid; therefore the hydrogen acts twice as fast, which represents the first real difficulty in combustion, because H by its rapid action prevents $CO_2$ from being formed, thereby encouraging the formation of CO or carbon monoxide, and CO spells loss to the final result.

In usual practice fuel is burnt by admitting air to the furnace generally by the ashpit, and as the air passes through the burning fuel $CO_2$ is formed. The hydrogen being the lighter gas, seizes the oxygen associated with the carbon above the fire, and CO is formed, because the hydrogen only requires 1 volume of O; whereas $CO_2$ requires 2 volumes, and as CO means 1 volume of carbon and 1 of oxygen, thus, the operation results in CO being formed in place of $CO_2$.

The usual practice is to distil off the lighter gas by piling the coal on one side of the dead plate, and if hydrogen is in excess of that required for $H_2O$, the residue, acting rapidly, seizes upon O in ad-

vance of the carbon, and the result is that H takes half of what C requires to form $CO_2$ and the result is CO and smoke.

This is most likely to occur when fresh fuel is applied, because the inrush of cold air lowers the general temperature, causing the draught to be sluggish. This at once checks the new air supply, and the gaseous product reaches the opening over the bridge denuded of part of its oxygen, whilst the hydrogen has combined with the other volume of O which, otherwise employed, would have resulted in $CO_2$ being formed, and the ideal condition would be reached.

Assume that all the elements necessary for perfect combustion are present in the furnace, whilst coal is distilling off the light gas, and H is in excess of that required for $H_2O$, the air coming through the incandescent fuel brings the oxygen into contact with the carbon, and $CO_2$ is delivered from the surface of the fire; then the excess hydrogen follows, and robs sufficient oxygen from $CO_2$ to suit its volume, resulting in lowering the quantity of $CO_2$ and increasing CO. This will lower the general temperature and still further promote smoke formation. This must be true, because a bright fire encourages the formation of $CO_2$ and a dull fire CO.

A dull fire always occurs if the fire door is left open, and the admission of cold air always causes a smoke volume to show.

If the volatile gases are being distilled off, the large volume of hydrogen, compared with the relatively small volume of air coming in through the door perforations, when admitted must impede

the velocity of the air and prevent it getting into the draught vortex, and the large hydrogen volume, being in front of the last air supply, is expanded by the heat which aids its search for oxygen, when it gets amongst the $CO_2$ gas above the fire, and presuming that no oxygen is present to combine with the H, it takes it from $CO_2$, leaving an enlarged amount of CO.

A somewhat similar effect may occur when carbon is given off by distillation and there is no oxygen to combine with it, then $CO_2$ must suffer to accommodate the excess carbon.

Now, CO will inflame at a low temperature; therefore the presence of CO means a low temperature flue gas of greater density than the other, so the movement toward the chimney is destroyed and the draught is reduced.

CO will inflame at the chimney top when it comes into contact with cold air, and it is that which produces the flame often seen at the chimney outlet of blast furnaces, also from the funnels of steamships.

In both cases it proves the loss of valuable heat, and it must be due to imperfect combustion.

The causes why carbon monoxide or CO is detrimental to economy, and the form it takes, and the value of its combination, are well known; but how to prevent its active formation under the complicated conditions found in a boiler furnace is one of the problems of combustion.

Probably, if this was the only difficulty some means of avoiding it might be forthcoming, but it is only one of many. In fact difficulty is met by

difficulty, and complexity mounts upon complexity, making economical combustion into one of the stiffest problems boiler experts are trying to solve.

It is practically impossible to even attempt a solution unless the nature and character of the gases found in a boiler furnace are known, or to comprehend the variety of combinations possible, until the names and affinities and their proportions are explained, for which reason the domain of the

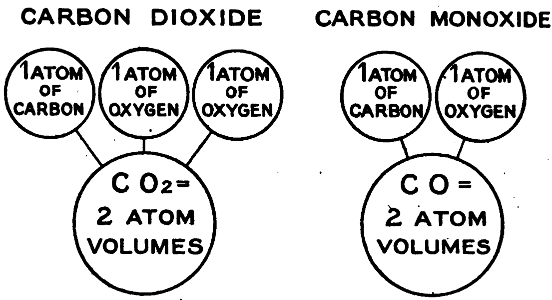



FIG. 13.

chemist must be invaded, and some of the secrets of the laboratory must be unveiled.

The compound gases arising out of combustion are fruitful causes of disturbance, in spite of the fact that one of the chief elements, carbon, has no separate vapour-volume, yet it must possess a vapour-volume when associated with another element.

The diagrams will aid the conception of the furnace difficulties, because volume influences the issue affecting the value of the gaseous products as heat vehicles for the two compound gases $CO_2$, carbon-dioxide, and CO, or carbon-monoxide.

As shown diagrammatically the carbon-dioxide

formation incorporates three equal volumes, one being carbon and two oxygen, or as separate volumes they equal say 1 cubic foot each, or a total of 3 cubic feet; but in combination the volume is only 2 cubic feet, and therefore the 2 cubic feet weighs as much as the three separate volumes.

The CO or carbon-monoxide, by its separate elements, equal one volume of each, and in combination, where each volume as a separate element is equal to 1 cubic foot, the combined gases weigh as much as the two separate volumes in the 2 cubic feet volume.

The amount of heat required to increase the temperature of a unit weight of $CO_2$ is ·217, whereas ·242 is required for CO. These are the specific heats as given by D. K. Clark, and it is quite obvious that a volume of $CO_2$, equal to a volume of CO, is the heavier; therefore more heat will be required to increase $CO_2$ in temperature 1° F. than would be needed to increase CO 1° F., even if the heat required was equal. Thus, it is quite evident that CO requires less heat to increase its temperature than $CO_2$ does.

This reveals, at a glance, one of the difficulties attending combustion.

One thing is evident, the supply of oxygen to the furnace is important, and air is the vehicle employed to introduce it; but it is accompanied by its fellow constituent nitrogen, which latter supplies the greatest volume, or as air is chiefly composed of the elements of oxygen and nitrogen, of which the largest volume is the latter, a furnace starved of air is short of oxygen, and this means a dull fire

and low efficiency. Now, smoke is an evidence of low efficiency and an inefficient air supply, and is a proof that heat is being wasted.

A very obvious method of aiding the formation of the most useful combinations of the gaseous products is by distilling off the volatile gases, whilst supplying the necessary oxygen to associate with them. The means to this end will be discussed at a subsequent stage, because on it rests part of the solution of how to obtain the best combustion.

Makers of mechanical stokers claim that the apparatus provides the remedy; whereas the real advantage of all mechanical devices is to feed minute quantities of fuel regularly and consistently, with the possibility of regulating the air supply to suit the quantity.

A variety of mechanical feeding apparatus are in existence, one being the chain-grate, which is taken as an illustration.

With the chain grate the hottest parts are brought into contact with the colder air in the ashpit, and the heat of the previous fuel is dissipated to the air, thereby increasing its temperature, enlarging its volume, which calls for an extra draught effect to compensate for the vitiated volume; whereas the ordinary furnace fire-bars lose heat downwards into the ash-pit, even as the travelling bars do likewise, but they lose nothing from their top surface; but they return the heat derived from previous fuel to fresh increments.

The chain-grate means cleaner bars and freedom from clinker, and the continual movement of fuel from the coldest to the hottest part of the furnace

serves a good purpose in keeping the bars clean. The open door is avoided, which is necessary, whilst clinkering and the inrush of cold air are prevented, but this is over a limited time; whereas the constant downward loss of heat from the hot surface of the travelling bars is practically equal to the loss of clinkering in hand stoking when the work is done by skilled labour.

There is, in the writer's opinion, not the least doubt that expert hand firing conducted with intelligence will show a greater economy for quantity of steam produced than any mechanical contrivance ever invented.

Unfortunately hand firing is usually relegated to men who can lift a shovelful of coal to keep a fire alive, but generally the result is not satisfactory, and it is just here where the advantage of mechanical stokers comes in, because they are more or less consistent to the conditions they are set to fulfil, and there is no laxity and no forgetfulness to mar the general result.

Therefore mechanical stokers supply a necessary want by ensuring a regular fuel feed in a given time, and travelling grates save the time of arduous cleaning which is too often slovenly done and sometimes neglected. Most forms of apparatus will pay because they keep up a steady supply of steam; but even plants fitted with mechanical stokers need intelligent supervision.

It is practically impossible to attain perfect combustion in a boiler furnace, because excess air is generally admitted; yet it is assumedly reached, or nearly so, when large quantities of fuel are burnt upon a given grate area.

Without air, combustion would be difficult if not impossible, therefore a knowledge of air and its properties is essential to all boiler users and designers.

*Atmospheric Air.*—Air is not entirely composed of oxygen and nitrogen, but the quantities are practically invariable. Minor quantities of other gases are present, though too small to be considered in this connexion.

As carbon and hydrogen are the chief elements in coal, so oxygen and nitrogen are the main constituents of air, and on these four chief elements the processes of combustion rest; but the chief difficulty is to get the oxygen element to where it will be of the most use, or rather to the place where the gases given off from the fuel can reach their affinity.

As already demonstrated gases combine in different proportions to form particular combinations, and 4 volumes of nitrogen mix with 1 volume of oxygen.

Air is a mixture of two main elements. A rough percentage composition is 80 per cent for N, and 20 per cent for O.

As a fact varying values are given, and a very usual value is 78·49 for N, and 20·63 for O for volume.

Another valuation is 74·5 per cent for N, and 27·5 per cent for O as volumes, and 77 per cent for N and 23 per cent for O, by weight.

Whatever the variety of combinations arising from the gases found in a boiler furnace, there is no known combination of N and O, because air is merely a mechanical mixture.

This assertion must be qualified because N and O

do combine in what is termed the nitric acid series; but whether these combinations have any effect on combustion as a continuous operation is doubtful; therefore it is sufficient to merely call attention to them.

One other combination to consider is ammonia found in coal, or $N.H_3$. Fortunately this is split up at a very ordinary temperature, in fact it is destroyed at anything above a red heat.

As the furnace temperature may be 2000° F., with fresh supplies of fuel the temperature rises quickly past the point where ammonia is destroyed; therefore it may be possible for N to combine when the conditions are suitable, but they can have little effect upon the final result, which is at a temperature a long way beyond that at which the N combination can exist.

Whilst the possible combinations are numerous, probably only three combinations need be considered, viz. CO or carbon-monoxide, $CO_2$ or carbon-dioxide, and $H_2O$ or water or steam.

As a molecular volume CO is equal to $CO_2$. If another atom volume of O is added to CO the result is $CO_2$, but there is no alteration of volume. As the addition of another atom volume of O causes the gas to give off more heat, it proves that CO is combustible, and as O cannot give off heat it is evident that C in CO is improperly, and only partially consumed, therefore if CO passes away with the waste gases useful heat is wasted.

Bringing the case down to a practical issue, where the estimated heat value of 1 lb. of coal is 14·700 B.Th.U., if the gaseous product is CO its value as

heat is only 4452, whereas as $CO_2$ the heat value is 14,700.

Thus the boiler user where combustion results in CO finds that only one-third of the possible heat is utilized, but where $CO_2$ results the whole heat is employed, and as this rests upon correct combustion, the carbon and oxygen formations require particular attention.

All gaseous products, in fact all forms of matter, are said to be composed of molecules, and the molecules are produced by a combination of atoms, therefore the atom volume requires consideration.

*Atomic Volume.*—Standards of comparison are needed, and just as water is the standard for relative weight, or gravity, so hydrogen is the standard for gaseous volume, and calling the volume 1, and its weight 1, comparison with other gases becomes possible ; for instance, an atom of carbon, assumedly as a gas, is only half the standard volume, but its weight is six times that of an equal volume of hydrogen, and as two atoms as half volumes of C are referred to one whole volume of H, so as H = 1 then C = 12, or its atomic weight for equal volumes is as 12 to 1.

An oxygen atom is only half the standard volume, but its weight for equal volumes referred to the standard is (16).

As the atom volume of nitrogen is four times that of oxygen, and oxygen is only half the atom size of H, and it follows that N atom volume is twice the size of the standard, and for equal volumes N is fourteen times as heavy, therefore H = 1 and N = 14.

For convenience these factors are utilized as follows :—

| Element | Atom | Equal Volume | Weight |
|---|---|---|---|
| Hydrogen | 1 | 1 | 1 |
| Carbon | 1 | 1 | 12 |
| Oxygen | 1 | 1 | 16 |
| Nitrogen | 1 | 1 | 14 |

all being referred to atmospheric conditions, for equal pressure and temperature.

The weights of the combinations referred to the standard volume are the sum of the separate atomic weights: for instance, $CO = 12 + 16 = 28$; but this refers to two volumes, therefore $28 \div 2 = 14$ being the atomic weight for a unit volume. For $CO_2$ we have a weight $12 + 2 \times 16 = 44$. It has two volumes $\therefore$ for unit volume we have $\frac{44}{2} = 22$.

Therefore the comparative weights for the three combinations, are

$CO$ or carbon monoxide = 14
$CO_2$ ,, ,, dioxide = 22
Atmospheric air = 14, correctly 13·9

In practice two substances are dealt with, viz. air and fuel, and from these many combinations are formed, which include carburetted hydrogen or "Marsh Gas" and bicarburetted hydrogen or "Acetylene," and these are mentioned because they always occur where coal gas is.

## CHAPTER X.

### HYDROCARBONS, RADIANT AND CONVECTED HEAT, DISTILLATION, ETC.

CARBURETTED hydrogen contains the two elements in the proportion of 4 of hydrogen and 1 of carbon; whereas bi-carburetted hydrogen involves 4 of H and 2 of C; therefore the aggregate volumes of the separate elements in the latter are greater than in the former, and it appears to follow that the formation of bicarburetted hydrogen must encourage the inrush of cold air to fill the space assumedly denuded; otherwise a vacuum would ensue which would reduce the chimney pull and mean a lower combustion efficiency. The condition is possible where the oxygen is starved by admitting the full volume, but of vitiated, or heated air.

Supposing the fire to be in a state of active incandescence when new fuel is inserted, then as decomposition ensues the freed gases expand to form a barrier between the gaseous volume beyond the bridge and the air entering, either by the grate openings or door perforations, or by both. As the air supply is superior to the chimney discharge in regard to energy the effect is to push forward the products of combustion by expelling part of the chimney volume, and at the same time it puts a check

upon the new supply of air. The inevitable result seems to be in the direction of producing hydrocarbons, and the first to form must be carburetted hydrogen, which only requires 10 of air to 15 required by the bicarburetted; but assuming that oxygen is still available, then by robbing the $CO_2$ formation the mischief is intensified, because carbon is carried away by the hydrocarbons, the carburetted being of less atomic weight than the bicarburetted, which is equal to the atomic weight of nitrogen.

Apparently hydrocarbons carry off carbon even as CO carries away unconsumed combustible.

This is equivalent to wasting fuel, because both radiant and convected heat is lost.

The valuable deduction arrived at is that much of the lost evaporation generally found must be credited to the furnace, therefore combustion is the all-important factor.

Fuel economy, where the largest evaporation is attained by burning 1 lb. of fuel, is unquestionably attained under slow combustion conditions, but it is at the sacrifice of quantity.

To obtain quantity of evaporation when burning large masses of fuel, and at the same time ensuring fuel efficiency, is the ideal conception of good combustion.

These various references suggest practical hints of considerable importance to the manipulator of furnaces, such as the truism that though impossible to prevent the formation of hydrocarbons, or carbon monoxide, it may be possible to destroy the first by encouraging the formation of $CO_2$ which inevitably reduces CO.

The end may be aided by having clean fire bars and fires, and disturbing the fire as little as possible, and attention to the following precautions:—

Fire often, quickly, and over the greatest surface.

Keep the doors shut, and when this is impossible, close them quickly.

Keep the ashpit clean and make it the main channel for a continuous air supply.

When disturbing the fire do so alternately, half at a time, on each side.

When using average bituminous coal, in fact any coal of the class, use the corners of the dead plate as a distilling place; but take care to allow sufficient air to precede the evolution of fresh gas, by projecting the air currents across the path the gases must take to reach the general vortex.

Attention to these points will go a long way to aid perfect combustion, and assist general economy.

Atmospheric air is necessary, but it must be admitted where it can be of the greatest use.

Merely arranging for a quantity of air without arranging for its distribution is bad in conception, and disastrous as a finish.

Too much air reduces the temperature of the fire, and too little air prevents combustion, and consequently a poor efficiency ensues.

The larger the air volume is the greater the body of nitrogen to be raised to the general temperature without any compensating advantage, for whatever the volume of nitrogen it must be expelled from the chimney, impregnated with the temperature common to the other gases.

In practice excess air seems to be unavoidable for

thin fires, so generally from 50 to 100 per cent excess is allowed, but 100 per cent seems unjustifiable, though 50 per cent may really be necessary.

A large air supply means a low temperature for the gaseous products, though the radiant heat quantity may be increased; but it is little use to increase that which cannot be used, and as a rule a very large part of the heat radiated from fuel is lost because it is impossible to provide sufficient furnace heating surface to absorb it, besides it is dissipated in other ways.

A white incandescent fire means relatively less radiant heat as to quantity, but more active as to effect, besides convected heat is increased and the products of combustion are hotter, and these can be utilized by increasing the heating surface, or condensing the gas, by curtailing the outlet and adding to the draught.

Attention to these various matters all tend to economize fuel and add to evaporation, because the formation of $CO_2$ is encouraged, and the greater its percentage value the more efficient the boiler.

*How air should be admitted by the furnace doors*, to obtain good results, is amongst one of the many factors leading to success.

For instance, distillation of new fuel should precede its distribution over the fire surface, and the corners of the dead plate just inside of the furnace door furnishes an admirable distilling plant.

The very usual practice is to admit air through perforations in the fire door, which can be regulated by a shutter; but the practice of admitting it through perforations placed in a door, at right angles to the

fire length, is opposed to reasonableness, and is absolutely wrong.

The gases distilled off the fuel are light and readily seek the active part of the furnace, i.e. at the bridge, and in their passage over the fire they displace the heavier carbon-dioxide, besides robbing it of part of its oxygen, resulting in producing CO instead of $CO_2$.

Further, hydrogen gas is a cold substance requiring much heat to raise its temperature, and its volume enables it to dominate considerable space, whereas associated with oxygen its volume is reduced by one half: therefore it is best to supply the oxygen at the earliest possible moment.

The very lightness of hydrogen gas as a free element, allows it to flow towards the bridge faster than the slower air behind it can stop its progress by associating it with oxygen. The result has already been mentioned.

By ensuring the air inlet at the door to take a course across the corner of the dead plate a veritable curtain of air is interposed between the volatile products of distillation and the general body of the gas above the fire; besides the distilled gases find their affinity in the curtain, and amalgamation with it reduces the actual volume one third, thereby inducing an extra inrush of air, and a reduction of the effort to push the gaseous products in the flues and chimney out into the atmosphere.

To prevent this only needs a V-shaped projection of the door in which perforations are arranged to direct the air across the corner of the dead plate and down and up to form an absolute screen. The manipulation of shutters gives the means of alternat-

ing the openings to whichever side the active distillation is in operation.

Two things result from the method. Smoke is prevented and combustion is aided.

Fig. 14 gives a good idea of the method viewed on the plan of the furnace.

When coal is distilling on corner A the slide D is open, and the air currents partaking of the general inside draught velocity stream across the corner as shown, presenting an actual curtain of air, which the volatile gases must pass before entering the body of the furnace.

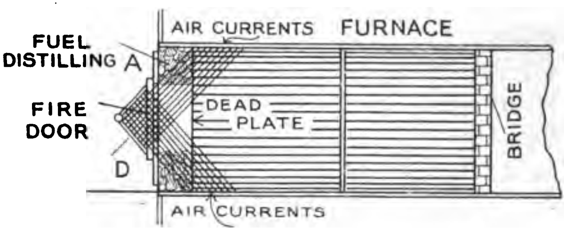



FIG. 14.

By alternately stacking the fresh fuel in alternate corners, and opening the inlet to correspond, and alternately pushing forward the earliest charge and distributing it over the surface, the fire is kept in a state of active incandescence and the gases at a corresponding high temperature; otherwise the diagram is self-evident. The air currents are heated by the heat gathered near the door, which otherwise would be lost, and the newly evolved gases are influenced in a similar way. The carbon element given off is likewise supplied with oxygen, independently of that which enters by the bar spaces, and is assumedly

converted into $CO_2$; therefore the danger of destroying a good fire by starving and of producing CO is avoided, and the final result is all in favour of superior combustion.

Mechanical stoking does not, and cannot, effect the same end. What it does is to make the disturbance continuous, and this means a less lowering of temperature over a short time, though a constant lower temperature always, with probably some little saving effected. The volatile gases still get into the general vortex at their elemental volume and unconsumed carbon is still carried off; but instead of being in noticeable quantity as seen by the smoke, it is represented by a very light-coloured vapour, scarcely perceptible, though nevertheless real.

Where 20 to 30 lb. of coal are burnt per square foot of grate per hour it is fed in continuously by the mechanical stoker, whereas, by hand firing, it may represent five lots, and that easily means perhaps five minutes of open door, and five times cooling down of temperature. This the mechanical stoker avoids, but only by spreading it out over the whole time of working. It prevents dense smoke, but it does not prevent CO from being driven off.

To see this it is only necessary to stand by an annealing oven when the door is first lifted a little, when a great curl of black smoke is evident, and in a similar way the space between the bars and the clearance for the top of the fuel produces a similar result. Indeed, by paying close attention to the entrance to a furnace of the travelling grate, the evolution of smoke can easily be discerned.

Evidently the right quantity of air arranged to

meet every new evolution of gas is the high road to fuel economy and boiler efficiency.

As a general statement the currents of air should move faster than the volatile gases can be given off by distillation, and this is reasonable because equal volumes of H and air are as 1 to 14 in regard to weight, and this, coupled with the natural avidity of hydrogen for carbon, makes it necessary for the air to move faster.

Lessons have been taught by experiment. In fact it may be said that present steam practice mainly rests upon the laborious process of trial and error, besides untold tests have provided data which are invaluable.

Tests for the relative efficiency of different fuels, the effect of different lengths of grate, for thin, medium, and thick fires, and means for the prevention of smoke, are amongst some of the purposes sought for.

Tests for the rate of consumption under varying amounts of excess air, even up to 100 per cent excess, have provided food for thought and incited ingenuity.

The deductions derived from such tests assume that 20 lb. of coal per square foot of grate requires 25 per cent excess air, and for 30 lb. 10 per cent excess which was found to be sufficient, and it is probable that higher rates of combustion may require no excess air, or that practically perfect combustion may be attained.

It has been demonstrated that thick fires, when burning bituminous coal, invariably give the best results, and short grates with thick fires have been

found superior to long grates when burning the same total quantity of fuel.

The effect of distilling off the volatile products prior to amalgamating them with the general body of burning fuel, in all cases showed an increased efficiency of from 3 to 4 per cent; whilst tests, with air in bulk and in streams, always showed an advantage for the latter; yet under either condition smoke can be prevented.

Admission of air, as excess, gave a better result when admitted by the bridge than by the door.

American and French engineers have not been one whit behind others in experimenting and observing, and such observations have completely broken down the assertions that the best had already been attained, by showing results which nobody anticipated.

The effect of mechanical appliances, the advantages of various alterations in structural form, and in fact nearly every conceivable method has been tried and experimented with to get better results than usual practice finds.

Saving smoke and economizing fuel has been a favourite claim, and even the genius of James Watt was not proof against it. He proposed to perform the operation by compelling the smoke to pass through flame made specially, also to pass smoke through hot tubes placed where the fuel was hottest, and then adding extra air.

A hundred years ago the wise method of admitting air in streams through openings in the fire door, also to compel air to pass over the fresh fuel placed on the incandescent mass before being pushed for-

ward towards the bridge, failed then and fails to-day, though it is not wanting in exponents.

A decade after this the panacea was to admit air by the bridge, but in spite of conduits, pipes, perforations, nozzles, etc., combustion was not improved.

Then came the period of baffles placed in the flues to compel the gases to take sinuous courses, some alternately decreasing and increasing the velocity, but all ended the same way, smoke still existed.

Following closely upon the baffle period came the hot air cure, and when that failed cold air was adopted, forced, and cajoled to traverse twists and turns and tortuous passages placed above and beneath, also through the firebars; indeed from every conceivable part, yet the cure was not effected.

Still another departure and another feverish period when perforated diaphragms, air inlets behind the fire into the combustion chamber, some in front, others behind, double grates with perforated bridges, twin furnaces; in fact nearly everything reasonable and unreasonable, but smoke could not be burnt economically.

Twenty-five to thirty years ago Livett introduced the enlarging flue, which increased in cross-sectional area as the gases were reduced in volume, and he certainly proved that there was an advantage, but the expense entailed was not commensurate with the advantage gained.

Messrs. Judd of St. Andrew's Hill, Ludgate, installed one, in fact two, and the efficiency was good. The boilers were easily examined, but the cost was

practically 50 per cent to 100 per cent more than the ordinary setting.

To mention only a very few of the boilers that were introduced, including all sorts and shapes of contorted elements, some to reduce the weight, others to improve efficiency, but all to make steam, would be interesting, if not instructive.

Through the whole gamut of form and style the Scotch marine boiler and the Lancashire emerge still, hard to beat as steam generators and smoke mitigators when properly handled.

Apparently the failure in all cases, or at least most, was the mistake of dealing with a detail rather than attacking the source of the evil.

That source is combustion, and the remedy has yet to be found.

## CHAPTER XI.

### COMBUSTION (*continued*).

Before attempting to trace the effect of heat through the various ramifications of a boiler, some knowledge of the value of heat energy and how to get the best out of it is necessary. Before combustion occurs, fuel holds heat energy in a potential state, and by combustion it becomes kinetic and useful.

The presence of heat is made known by various effects, particularly by addition or subtraction from some substance be it gaseous or solid. It is capable of making water boil, will melt ice or metals by increasing the temperature, and inversely, by its subtraction, it freezes water and solidifies metals.

Whatever hypothesis the scientist may rely upon to account for heat, it is enough for the present purpose to know that it exists, and its effects can be utilized to a useful purpose.

Substances said to be elastic, such as gases, obtain their property from heat which makes them expand by its addition and contract by its withdrawal.

The temperature of a body does not measure its real heat value, because different bodies require different amounts of heat to bring them to the same temperature.

One quantity of heat in a given volume may

show a very low temperature, whereas the same quantity in a small body may indicate a high temperature.

For one temperature, for 1 cubic inch of substance, the heat contained is 1, whereas for the same temperature in 1 cubic foot the heat value is 1728 times; therefore it is correct to say that temperature is no criterion of the quantity of heat a body holds, though temperature, for a unit determination, will enable the quantity of heat to be determined if size is considered.

Referring to heat in terms of the thermometer markings, such as 32, 62 or 80° F., readily gives an idea of the actual heat present, because a unit weight of substance requires a given amount of heat to add 1° F. to its temperature; therefore as the number of units in the body to be valued is in proportion to the weight in the supposed unit body, the actual heat value is easily determined.

When heat is added to a substance, either the volume or pressure is increased according to the conditions whether the substance is under constant pressure or constant volume. The value of such increase has been determined by experimentalists, whose labours on behalf of science are of incalculable value.

M. Regnault and M. Rudberg, as a result of many experiments, found that invariably a volume of a gas, raised from 32° F. to 212° F., increased from 1 to 1·365, or an increase of ·365 of the original; or each degree added to the temperature increased the volume $\frac{1}{493}$ times, and this was verified up to 700° F., and presumedly, inversely, the volume

would decrease by $\frac{1}{493}$ for every degree taken from the substance. The starting point is 32° F. and each degree of reduction represents $\frac{1}{493}$.

Now the thermometer markings are purely arbitrary, derived from actual experiment. Ice melts at one temperature and water boils at another, and these two points are termed zero and boiling-point. For arbitrary reasons the former for the Fahrenheit scale is marked 32, and the latter 212°.

If the law in regard to increase or decrease of volume by the addition or subtraction of 1° F. is invariable, then as each degree abstracted reduces the volume $\frac{1}{493}$, it follows that the abstraction of 493° F. would bring the substance down to a condition where there was neither heat nor volume.

Adding heat in the given proportion would increase the volume; therefore for general purposes it is said that increasing the temperature from 0° F. to 1° F. adds $\frac{1}{461}$ volumes to the original. It has likewise been determined, also by experiment, that a similar law applies to pressure where the temperature changes by 1° F. from 0° F., it increases the pressure $\frac{1}{461}$ times, or reduces it in a similar proportion.

The temperature obtained by adding 461 to the ordinary Fahrenheit reading is called the *absolute* Fahrenheit temperature.

Addition of heat either adds to pressure or volume, and always to temperature, except, as in the case of water, when changing from solid to liquid or liquid to gas where the temperature keeps constant while heat is being added.

For instance if 1° F. is added to a gas already indicated by 100° F. under constant pressure, the absolute temperature equals $100 + 461 = 561°$ F.; therefore the expansion by adding 1° F. equals $\frac{1}{561}$ times, or in proportion to its absolute temperature, and so on.

For substances held at constant volume, temperature, and pressure increase, and the greater the temperature the less is the actual increase of pressure as a proportion.

To prevent any misunderstanding let it be assumed that the previous remarks refer to gases alone.

As changes of temperature, volume, and pressure will be referred to at subsequent periods, the rules applicable to the various cases are given here in the form originally given by Mr. D. K. Clark.

"*Rule* 1.—*To find the new volume for a given weight of gas under constant pressure for any temperature.*

"Multiply the given volume by the new absolute temperature, and divide the product by the given absolute temperature, and the quotient is the new volume.

"*Example.*—1 lb. of gas with a volume of 12 cubic feet at 32° F.; what is its volume at 100° F.?

$$\text{New Volume} = V = \frac{12 \times (100 + 461)}{(32 + 461)}$$

$$= \frac{12 \times 561}{493} = 13{\cdot}65 \text{ cubic feet.}$$

"*Rule* 2.—*To find the volume for a constant weight of gas under a given pressure for another pressure, the temperature remaining constant.*

"Multiply the given volume by the given pressure

and divide by the new pressure; the quotient is the new volume.

"*Example.*—1 lb. of gas with a volume of 12 cubic feet under a pressure of 100 lb. per square inch; find the volume for 32 lb. pressure

$$V = \frac{12 \times 100}{32} = 37{\cdot}5 \text{ cubic feet.}$$

"*Rule* 3.—*To find the new volume for a constant weight of gas for another pressure and temperature, when the volume is known for a given pressure and temperature.*

"Multiply the given volume by the given pressure, and by the new absolute temperature, and divide the product by the product of the given pressure and absolute temperature.

"*Example.*—1 lb. of gas with a volume of 12 cubic feet, pressure 100 lb., temperature 300° F.; find the new volume for a pressure of 32 lb. and temperature 60° F.

$$V = \frac{12 \times 100 \times (60 + 461)}{(300 + 461) \times 32} = 15{\cdot}8 \text{ cubic feet,}$$

the new volume."

Other interpolations of the rules are evident, and as they require no more knowledge than is found in the rule of three, they become of great value to many, to whom formulæ are practically a dead language.

Mr. D. K. Clark in his "Manual of Tables," etc. defines the relation of pressure, volume, and temperature in a condensed form, based on the fact that the product of volume and pressure of one weight of gas is in proportion to the absolute temperature.

The condensed formula is, $Vp \div (t + 461)$ and as

the products to the absolute temperature have an invariable ratio an equation is possible. This is equal to the absolute temperature multiplied by a coefficient, say ($a$). Then $Vp = a(t + 461)$, which means that the product of volume and temperature is equal to the absolute temperature multiplied by a constant.

An application of the formula is referred to 32° F. and 14·7 lb. pressure, and assuming the volume of air = 12·387 cubic feet, then $12{\cdot}387 \times 14{\cdot}7 = 493 \times a$.

Now V = 12·387 and P = 14·7 = a product of 182·0889, being one side of the equation, and $t = 32 + 461 = 493$ is the other, and $182{\cdot}0889 \div 493 = {\cdot}36935$, or $\frac{1}{2{\cdot}7074}$, then the formula becomes

$$Vp = \left(\frac{t + 461}{2{\cdot}7074}\right).$$

*Note.*—The volumes are in cubic feet terms, and the pressures per square inch.

Appended is a table given by Mr. D. K. Clark, but it is only introduced to exemplify the application of the formula. It is of little use in the present connexion, but it helps to illustrate the concise character of the deduction, and will be useful as a reference if required.

| Name. | Volume per lb. at 32° F. and 14·7 lb. pressure. Cubic feet. | Coefficients of ($a$). |
|---|---|---|
| Hydrogen | 178·83 c. ft. | 5·33200 or $\frac{1}{0{\cdot}1875}$ |
| Gaseous steam | 19·91 „ | ·59372 „ $\frac{1}{1{\cdot}6842}$ |

| | | | | |
|---|---|---|---|---|
| Nitrogen | 12·72 | ,, | ·37937 ,, | $\frac{1}{2·6359}$ |
| Olefiant Gas | 12·58 | ,, | ·37506 ,, | $\frac{1}{2·6662}$ |
| Air (atmospheric) | 12·38 | ,, | ·36935 ,, | $\frac{1}{2·7074}$ |
| Carbon dioxide (ideal) | 8·15 | ,, | ·24322 ,, | $\frac{1}{4·1114}$ |
| ,, ,, (actual) | 8·10 | ,, | ·24155 ,, | $\frac{1}{4·1399}$ |
| Ether Vapour | 4·77 | ,, | ·14246 ,, | $\frac{1}{7·0195}$ |
| Vapour of Mercury | 1·77 | ,, | ·05296 ,, | $\frac{1}{18·878}$ |
| Oxygen. | 11·20 | ,, | ·33406 ,, | $\frac{1}{2·9935}$ |

*Combustion Effects.—Radiant heat* is said to be responsible for about 50 per cent of the total evaporation, and all of it is credited to the furnace heating surface. Its action is direct and effective, but it does not have any direct effect upon a gas.

Unfortunately all radiant heat is not engaged in useful work, and the great loss compared with the estimated heat value of the combustible is hard to account for.

When burning fuel in conjunction with atmospheric air the temperature of the fire is the first consideration, but in spite of vast experience, fire temperature and its effect in the production of radiant and convected heat leaves much to guess-work, yet it is practically impossible to say what the actual values of radiant and convected heat are, and as a consequence mere trial and error determines the amount of heating surface assumed to be necessary, because mathematical calculation is practically impossible.

Radiant heat is derived from fire surface, and

is expended upon the heating surface opposed to its movement, upon which it falls.

If the real value of radiant heat could be measured, the heating surface required to absorb it could be provided; or where the maximum furnace heating surface is provided radiant heat could be provided to get the greatest effect with the least loss, but this is not known with any certainty, therefore it is impossible to say what the maximum useful effect is, or how much in excess of actual furnace requirements could be saved by correct manipulation of combustion.

There is not much difficulty in determining the value of the heat in the products of combustion; therefore the difference between the estimated heat value of the fuel and what practice proves is usually credited to radiant heat.

The fact is that the results attained by combustion are largely speculative; therefore any analysis of furnace and boiler effects must be speculative also.

No one doubts that fire temperature influences the quantitative value of radiant and convected heats; their value in B.Th.U. terms is important, and many have turned their attention to the problem with the idea of solving it, but M. Peclet may be credited with having done more in this direction than any other scientist. Yet even he did little more than popularize the formula others had deduced, derived from data experiment provided.

M. Peclet had to fall back upon trial and error to assist him in determining the temperature that fitted closest with a known estimated heat value in

establishing formulæ. Whatever may be said of the rule, it is practically the only one capable of getting near the determination of the aggregate value of two heats which represent, in some proportion, the estimated heat value of a fuel.

In this case it is impossible to supply any simple explanation of the formula; therefore it must be given *in extenso*, and the ultimate use of the rule is to provide material for a table of heat quantities and temperatures which must be of considerable value to all engaged in boiler practice.

M. Peclet's rule is as follows:—

$R = 144\ a^{\phi}(a^{t} - 1)$ where $R$ = the quantity of radiant heat derived from 1 square foot of fire surface in B.Th.U. terms.

$\phi$ is the temperature of the contents of the boiler (°F.).

$t$ the excess temperature of the furnace side, over that of the water side of the plate (°F.).

$a$ is a constant = (1·00425).

Applying the rule to an assumed furnace temperature of 2000° F., steam temperature 328° F., air 62° F. the difference, or ($t$) = 2000 − 328 = 1672° F. This is assumed for 12 lb. of coal per square foot.

The formula becomes

$R = 144 \times 1{\cdot}00425^{328} \times (1{\cdot}00425^{1672} - 1)$, and by the use of a table of logarithms the final calculation gives an assumed radiant heat value of 695,000 units.

Let 14,700 B.Th.U. be the estimated heat value of 1 lb. of coal, then 14,700 × 12 = 176,400 units, which is only about one-fourth of the ascertained radiant heat value; therefore the temperature cannot be 2000° F.

Assuming the temperature is 1500° F.; if worked out on the lines given, radiant heat is assumed to be 85,453 units.

For convected heat, assuming the fuel temperature to be 62° F. we have a temperature difference of $1500 - 62 = 1438$ representing the rise in temperature of the gases supposed, and suppose 4·131 units per lb. of fuel are required to raise the gases through 1° F., then $4{\cdot}131 \times 12 = 49{\cdot}572$ units $\times 1438 = 71{,}284$ units of convected heat + 83,453 units of radiant heat = 154,737 units, or about 87 per cent of the estimated heat value; therefore the temperature must be between 2000 and 1500° F.

Assuming the temperature to be 1550° F. and applying the formula, the worked out values fit the estimated heat value of the fuel; therefore the temperature of the surface of the fire is 1550° F.

The example is fully worked out as follows:—

The difference is $1550 - 328 = 1222$° F. and the formula becomes

$$R = 144 \times 1{\cdot}00425^{328} \times (1{\cdot}00425^{1222} - 1).$$

The logarithm of 1·00425 = ·001842 (taken from a table of logarithms), and multiplying by 328 to get the 328th power = ·604176, and the number or antilogarithm we have = 4019, and as there is no integer before the decimal point only 1 unit is marked off or = 4·019.

In a similar way $\cdot 001842 \times 1222 = 2{\cdot}250924$ = the logarithm of the 1222th power, and the number = 1782, and with 2 as the integer, 3 places before the decimal point gives the actual value of the number; or 178·2.

Then $R = 144 \times 4{\cdot}019 \times (178{\cdot}2 - 1) =$ by re-

duction R = 578·736 × 177·2 = 102,552 units, the value of radiant heat.

The temperature due to the combustible = 1550 − 62 = 1488° F., and where 4·131 units are required per lb. of coal to raise the gases 1° F., then 4·131 × 12 × 1488 = 73763 units convected heat + 102,552 = 176315; or within 85 units of the estimated heat value of the fuel.

By such methods the relative values of radiant and convected heat can be estimated; besides the temperature of the fire is determined.

Mr. D. K. Clark, in his treatise on the steam engine, furnishes a table of temperatures and heat values for increasing quantities of fuel, and from it he draws the deduction that radiant heat only increases as the ·972 power of the rate of consumption.

Clark's table is arranged for ideal combustion for natural draught conditions, whereas the usual practice is to permit the introduction of 50 per cent excess air; therefore a new table has been specially compiled by the author to suit the 50 per cent excess condition.

The estimated heat value of the fuel is taken in both cases as 14,700 units; but the temperature of combustion for the 50 per cent excess is about 3293° F., whereas for Clark's it is 4559° F.

Clark's table supposes complete combustion, no excess air, and estimated heat value per lb. of coal = 14,700 units.

### MR. D. K. CLARK'S TABLE.

Temperature of Combustion about 4560° F.

| Coal consumed per hour per sq. ft. of Grate | Temperature of Inside of Plate $\phi$ | Temperature of the Plate Furnace Side $t$ | Radiant Heat R | Convected Heat C | Sum of R + C | Total Heat of Combustible |
|---|---|---|---|---|---|---|
| Lb. | °F. | °F. | Units | Units | Units | Units |
| 5 | 350 | 1400 | 52,960 | 19,160 | 73,120 | 73,500 |
| 10 | 350 | 1550 | 102,500 | 43,510 | 146,010 | 147,000 |
| 20 | 350 | 1705 | 198,400 | 96,080 | 294,480 | 294,000 |
| 40 | 350 | 1857 | 378,650 | 209,850 | 588,500 | 588,000 |
| 80 | 350 | 2009 | 721,800 | 455,400 | 1,177,200 | 1,176,000 |
| 120 | 350 | 2097 | 1,049,000 | 714,050 | 1,763,050 | 1,764,000 |

As a means of comparison, and to show the effect of 50 per cent excess air, the subjoined table is introduced.

### AUTHOR'S TABLE.

Coal 14,700, B.Th.U. Temperature of Combustion about 3293° F.

| Coal consumed per hour per sq. ft. of Grate | Temperature of Inside of Plate $\phi$ | Temperature of the Plate Furnace Side $t$ | Radiant Heat R | Convected Heat C | Sum of R + C | Total Heat of Combustible |
|---|---|---|---|---|---|---|
| Lb. | °F. | °F. | Units | Units | Units | Units |
| 5 | 328 | 1366 | 46,669 | 29,930 | 73,599 | 73,500 |
| 10 | 328 | 1512 | 87,215 | 59,899 | 147,114 | 147,000 |
| 12 | 328 | 1550 | 102,552 | 73,763 | 176,315 | 176,400 |
| 15 | 328 | 1597 | 125,353 | 95,155 | 220,468 | 220,500 |
| 20 | 328 | 1658 | 162,451 | 131,860 | 294,311 | 294,000 |
| 40 | 328 | 1803 | 301,000 | 287,680 | 588,680 | 588,000 |
| 80 | 328 | 1946 | 552,519 | 662,079 | 1,176,374 | 1,176,000 |
| 120 | 328 | 2030 | 790,335 | 975,557 | 1,764,305 | 1,764,000 |

The addition of 50 per cent excess air reduces the temperature of combustion considerably, and in this connexion a condition forms one of the problems of combustion. Whether it is mere coincidence or establishes a rule matters not, but it is worth examining, because 50 per cent excess air $= 5{\cdot}3$ lb. $\times 12 = 63{\cdot}6$ lb. for 12 lb. of coal consumed, and taking the specific heat as ·2377, 15·1 units are required to increase the temperature 1° F. and $1488 \times 15{\cdot}1 = 22{,}468$ units, or roughly about 33 per cent of the convected heat is used by the excess air for a fire surface temperature of 1550° F.

The difference between the temperature of combustion for the assumed perfect condition, and that when 50 per cent excess air is introduced is close upon 1267° F., and it needs no argument to see that the reduction is due to the excess air supply.

Whilst the fire surface may be 1550° F., or the average temperature of the contents above the surface of the fire are assumed to be at that temperature, the body of the fire may be much more, even as the actual surface of the fire may be more than 1550° F.

Presumedly, when burning 12 lb. of coal per square foot of grate the general body of the fuel as an average may be over 2000° F., whether it is for perfect combustion or excess air.

If 33 per cent of the convected heat is taken up by the excess air, it is safe to say that a corresponding amount of the radiant is restrained from acting.

Now, if 33 per cent of the available heat units are absorbed by excess air the temperature of combustion can only be in proportion. This may roughly

account for the difference between the temperature for perfect combustion and that with 50 per cent excess air.

The cause can scarcely be due to excess CO formation because the air supply is in excess of $CO_2$ requirements ; but the lower temperature may restrain the carbon delivery whilst the volatile gases are readily given off, and these can associate with the extra oxygen to form hydrocarbons to be carried away in the excess volume without doing useful work.

Another view may be taken, and perhaps that is more reasonable, viz. under perfect combustion conditions the whole of the carbon and hydrogen constituents are forced to decompose from the fuel, and the ideal condition is reached in which the flue gases comprise only nitrogen, and the gaseous products.

This shows the disadvantage of too much air, because it reduces the fire temperature, and increases the proportion of radiant heat to convected heat though both suffer quantitatively. The increase of radiant heat at the expense of the convected heat is not productive of economy because it cannot be usefully employed.

Nothing more is claimed for this view than that excessive air supply is not conducive to economy. But excess air has such a marked effect on the final result that it must be considered, and that can only be done speculatively.

Now, for perfect combustion 1 lb. of coal of 14700 B.Th.U. (estimated) requires 10·7 lb. of atmospheric air, which results in the production of 11·7 lb. of gas. The specific heat, referred to the weight of gas = 2·9

units which are required to raise the temperature 1° F.

Under the rule, for a temperature of 1553° F. radiant heat equals 103,883 units, and convected heat 43,239 units, equal to a total of 147,122 units, or close to the estimated fuel value for 10 lb. of coal per square foot of grate, for perfect combustion.

The addition of 50 per cent excess air reduces the fire temperature to 1512° F. and raises the unit value per degree of temperature, from 2·9 units to 4·131 units, or a ratio of 1 to 1·42.

Assuming that 50 per cent of the total water evaporation is credited to radiant heat, and 10 per cent of the convected heat is carried off in the waste gases, a comparative effect can be deduced though it is a gross effect and not net.

With the 50 per cent excess air an extra efficiency of 18 per cent seems to occur: but for the same furnace temperature 12 lb. of coal is used instead of 10: or 16·7 per cent more fuel increases the efficiency to 18 per cent or 1 3 per cent better.

Assuming that 50 per cent excess air is equivalent to 48 per cent greater gas volume, then 1·48 volumes must pass through the flues in the same time as 1 volume, therefore the velocity of the larger volume must either be faster than the other, which means a greater draught, though it is not consistent with a lower temperature, or the larger volume must be condensed.

But the 1 volume is at a temperature of 1553, and the larger volume at 1512, therefore as (1553 + 461) : (1512 + 461) :: 1·48 : ·95; therefore the volumes are practically equal, and their rate of movement is

the same through the flues, and presumedly the evaporation is as their respective temperatures.

The radiant heat for the assumed 50 per cent furnace efficiency comes to 102,500 units; therefore the furnace efficiency for a lower radiant heat value is presumedly in proportion or as 102,500 : 87,215 : : 50 : 42 per cent, or 8 per cent less. Then 8 taken from 70 leaves 62 per cent, the efficiency with 50 per cent excess air, and this closely approximates to good practice in boilers of the Lancashire type.

Probably perfect combustion with the higher temperature increased the efficiency of the furnace heating surface, and assuming this to be in proportion to the estimated radiant heat values the difference is 15 per cent; but the increase refers to all radiant heat of which possibly one-third is discharged into the ash-pit by the fire-bar spaces and the ends of the fire radiate heat to the fire door and bridge; besides some is credited to the gaseous product which is, in fact, supplementary to it, which is due to heat radiated diagonally to the surface behind the bridge.

Considering these various distributions the extra radiant heat effect may represent 5 to 7 per cent; bringing the efficiency up to say 60 per cent of the estimated fuel value.

In one way or the other, in practice, allowing 50 per cent excess air may conditionally show an increased efficiency of 2 to 3 per cent.

On such lines combustion must be considered, and the deductive values are probably very near to

possible conditions for good practice in boilers of the Lancashire type.

The method is necessarily speculative, but it teaches one great lesson that efficiency rests upon a proper understanding of what combustion means.

## CHAPTER XII.

### TEMPERATURE, ETC.

FOLLOWING up the question of temperature and the respective values of radiant and convected heat may meet a demand for something more reliable than practice generally provides, and to that end the following matter is introduced, and it is hoped that the rather full tables included will repay the trouble expended on their production.

MM. Dulong and Petiet were the original experimenters, although M. Peclet framed the formula as already explained.

*Temperature of Combustion* requires consideration first, and it is based upon the assumption that if the whole heat of combustion was utilised in heating the products the result would give the greatest maximum temperature possible from the fuel. In practice it is never reached, that is in boiler practice, though it is approximately found in the reverberatory furnace, under special conditions.

In all cases in the present book the estimated heat value of 1 lb. of coal is taken as 14,700 B.Th.U.

Now, 1 lb. of such coal, for perfect combustion, gives 11·7 lb. of gaseous product of which

| | | | | | |
|---|---|---|---|---|---|
| 0·4 | lb. is gaseous steam whose specific heat is | | | | ·475 |
| 2·9 | ,, of carbon-dioxide | ,, | ,, | ,, | ·216 |
| 8·31 | ,, of nitrogen | ,, | ,, | ,, | ·244 |

and by reference to their respective weights the heat required to increase the temperature of the total products 1° F. is found as follows :—

| | | | | |
|---|---|---|---|---|
| Gaseous steam, | or $H_2O$ = 0·4 | lb. | × ·475 | = ·190 |
| Carbon-dioxide, | or $CO_2$ = 2·94 | ,, | × ·216 | = ·635 |
| Nitrogen, | or N = 8·31 | ,, | × ·244 | = 2·027 |

Now, the total = 2·854, and allowing ·026 for that required for the remaining weight, the total is 2·878 ÷ 11·7 = say ·246 the average specific heat.

The estimated heat value is derived from 80 per cent of carbon, 5 per cent of hydrogen, 8 per cent of oxygen, and 7 per cent of other gases; therefore the estimated value merely takes account of carbon, hydrogen, and atmospheric air.

The estimated heat value of the fuel divided by the number of units required to raise their temperature 1° F., or 14,700 ÷ 2·878 = 5108° F. plus 62 temperature of atmosphere = 5166° F. the total temperature of combustion (approximate). This temperature is different because the estimated value is based on other conditions than those referred to in Clark's Table.

As a preparation to the compilation of a table of temperatures and heats for increasing quantities of coal burnt by combustion on 1 square foot of grate area, perfect combustion is assumed.

A rate of 5 lb. of coal per square foot of grate presumes a temperature of 1400° F., and the values of radiant and convected heat are taken as the foundation for other determinations supplied by the table.

From an examination of Clark's table on page 125 the temperatures for different quantities of fuel

increase in the following order, by doubling the amount of fuel burnt in 1 square foot of grate.

| From (lbs.) | Tem. °F. | To. (lbs.) | Tem. °F. | Difference. °F. | Rate per lb. increase on °F as a proportion. °F. |
|---|---|---|---|---|---|
| 5 | 1400 | 10 | 1550 | 150 ÷ 5 = | 30° |
| 10 | 1550 | 20 | 1705 | 155 ÷ 10 = | 15·5° |
| 20 | 1705 | 40 | 1857 | 152 ÷ 20 = | 7·6° |
| 40 | 1857 | 80 | 2009 | 152 ÷ 40 = | 3·8° |
| 80 | 2009 | 120 | 2097 | 88 ÷ 80 = | 1·1° |

Obviously the starting temperature may be referred to 0° F., and 1400° F. ÷ 5 = 280° F. the increase for each 1 lb. of fuel, added to the quantity burnt at the 5 lb. rate.

Now, 1400° F. may be taken as the working temperature, though many boiler furnaces indicate less, but always at a disadvantage, and they exhibit a low economy.

The rise from 0° F. to 1400° F. is indicated by the diagram as follows :—

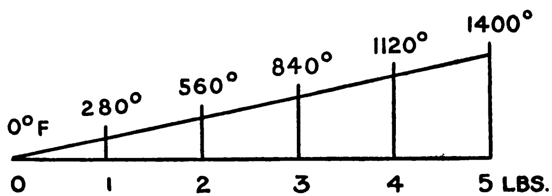



FIG. 15.

The vertical lines indicate the rise of each succeeding lb. Bringing down the increasing quantities burnt whilst adding the increasing temperature per lb. of increase, the approximate or final temperatures for the given quantities are shown, and these tem-

peratures are found approximately by attention to M. Peclet's rule.

The principle on which the following table is based refers to the ratio of the average temperature, as per diagram, plus the average increased temperature, due to the difference between the single and double consumption rates, and the sum is the value for each increased 1 lb. or multiple of it for double consumption, or as follows:—

The previous diagram refers to burning 5 lb. of coal per square foot of grate and the surface temperature is 1400° F., and it is arbitrarily assumed that each lb. contributes 280° to the final result, and $280 \times 5 = 1400°$ F.

By doubling the quantity of fuel burnt on an equal surface the surface temperature is increased 150°, divided by the increased fuel equals 30° per lb., and this, added to the previous division, increases the proportion that each extra lb. supplies to $310° \times 5 = 1550°$ F. By such deductions the table is produced, being the result of dividing increased fire surface temperature by the increased consumption. For instance, the temperature for 5 lb. burnt is 1400° F. and for 10 lb. an increase of 150, and the increase 5 divided into $150 = 30$, the increase per lb. Now the increased temperature due to doubling the quantity of fuel is 155, and the rate is 10 lb. per square foot divided into $155 = 15{\cdot}5$; but 10 is twice 5, therefore it is equal to $10 \div 5 = 2$, and $15{\cdot}5 \times 2 = 31°$, the increase, plus the previous rate, equal $341° \times 5 = 1705°$ F., and so on. The method adopted is convenient to find a rate that will be in proportion to the increased consumption.

| Consumption. | Ratio rise per lb. | | | | |
|---|---|---|---|---|---|
| 1. From 1 to 5 = 1 lb. increase | 280 | 560 | 840 | 1120 | 1400° F. |
| 2. rate 30° F. = | 30 | 60 | 90 | 120 | 150° F. |
| 1. From 5 to 10. | 310 | 620 | 930 | 1240 | 1550° F. |
| 2. rate 15·5 × 2 = 31° F. = | 31 | 62 | 93 | 124 | 155° F. |
| 1. From 10 to 20 | 341 | 682 | 1023 | 1364 | 1705° F. |
| 2. rate 7·6 × 4 = 30·4 = | 30·4 | 60·8 | 91·2 | 121·6 | 152° F. |
| 1. From 20 to 40 | 371·4 | 742·8 | 1114·2 | 1485·6 | 1857° F. |
| 2. rate 3·8 × 8 = 30·4 = | 30·4 | 60·8 | 91·2 | 121·6 | 152° F. |
| 1. From 40 to 80 | 401·8 | 803·6 | 1205·4 | 1607·2 | 2009° F. |
| 2. rate 1·1 × 16 = 17·6 = | 17·6 | 35·2 | 52·8 | 70·4 | 88 |
| Total | 419·4 | 838·8 | 1258·2 | 1677·6 | 2097° F. |

It is quite probable that the actual variation may run in regular sequence, as 30, 15, 7·5, 3·75, 1·875, and each of these multiplied by their increase referred to 5 as the starting factor will probably give the result; but the present object is to provide useful information in which the results are approximately correct, rather than to analyse deductions already accepted as reasonably correct.

The consistency of the final temperatures for the given final quantities, for the doubled increase, fits in with the temperatures found by M. Peclet's rule, showing that the present deduction is based on an accurate determination.

Assuming that the temperatures of the fire surface increases as the ratio table, then the temperatures for each 1 lb. increase are as follows, but the increased temperatures are based on the conditions found, by doubling the quantity of fuel burnt in succeeding stages, as for instance, 5, 10, 20, 40, 80 lb.

Based on these deductions the approximate temperatures are given from 5 to 80 lb. of coal consumed per square foot of grate.

| | | | | | | |
|---|---|---|---|---|---|---|
| From Temp. | 5 lb. 1400° F. | 6 lb. 1430° F. | 7 lb. 1460° F. | 8 lb. 1490° F. | 9 lb. 1520° F. | 10 lb. = 1550° F. |
| From Temp. | 11 lb. 1565·5° F. | 12 lb. 1581° F. | 13 lb. 1596·5° F. | 14 lb. 1612° F. | 15 lb. 1627·5° F. | 16 lb. = 1643° F. |
| From Temp. | 17 lb. 1658·5° F. | 18 lb. 1674° F. | 19 lb. 1689·5° F. | 20 lb. 1705° F. | 21 lb. 1712·6° F. | 22 lb. = 1720° F. |
| From Temp. | 23 lb. 1727·8° F. | 24 lb. 1735·4° F. | 25 lb. 1743° F. | 26 lb. 1750·6° F. | 27 lb. 1758·2° F. | 28 lb. = 1765·8° F. |
| From Temp. | 29 lb. 1773·4° F. | 30 lb. 1781° F. | 31 lb. 1788·6° F. | 32 lb. 1791·2° F. | 33 lb. 1805·8° F. | 34 lb. = 1813·4° F. |
| From Temp. | 35 lb. 1821° F. | 36 lb. 1828·6° F. | 37 lb. 1836·2° F. | 38 lb. 1843·8° F. | 39 lb. 1851·4° F. | 40 lb. = 1857° F. |
| From Temp. | 41 lb. 1860·8° F. | 42 lb. 1864·6° F. | 43 lb. 1868·4° F. | 44 lb. 1872·2° F. | 45 lb. 1876° F. | 46 lb. = 1879·8° F. |
| From Temp. | 47 lb. 1883·6° F. | 48 lb. 1887·4° F. | 49 lb. 1891·2° F. | 50 lb. 1895° F. | 51 lb. 1898·8° F. | 52 lb. = 1902·6° F. |
| From Temp. | 53 lb. 1906·4° F. | 54 lb. 1910·2° F. | 55 lb. 1914° F. | 56 lb. 1917·8° F. | 57 lb. 1921·6° F. | 58 lb. = 1925·4° F. |
| From Temp. | 59 lb. 1929·2° F. | 60 lb. 1933° F. | 61 lb. 1936·8° F. | 62 lb. 1940·6° F. | 63 lb. 1944·4° F. | 64 lb. = 1948° F. |
| From Temp. | 65 lb. 1952° F. | 66 lb. 1955·8° F. | 67 lb. 1959·6° F. | 68 lb. 1963·4° F. | 69 lb. 1967·2° F. | 70 lb. = 1971° F. |
| From Temp. | 71 lb. 1974·8° F. | 72 lb. 1978·6° F. | 73 lb. 1982·4° F. | 74 lb. 1985·2° F. | 75 lb. 1990° F. | 76 lb. = 1993·2° F. |
| From Temp. | 77 lb. 1997·6° F. | 78 lb. 2001·4° F. | 79 lb. 2005·2° F. | 80 lb. 2009° F. | | |

The table is for perfect combustion, which is not usually found in practice, except, perhaps, when burning very large quantities of fuel under forced draught conditions, therefore it is necessary to supply a method to enable the temperature to be found for excess air, based upon 50 per cent excess.

The following deductions closely approximate to those found by M. Peclet's rule :—

| | | | | |
|---|---|---|---|---|
| From | 5 to 10 lb. | deduct | 2·5 | per cent |
| | 10 to 20 „ | „ | 2·5 | „ |
| | 20 to 40 „ | „ | 2·8 | „ |
| | 40 to 80 „ | „ | 3·2 | „ |

For less or more excess air the reductions in per cent terms are taken in proportion, and the results will closely approximate to the rule.

A table of radiant and convected heat values is introduced for perfect combustion ; but by the aid of the table of temperatures and a constant, the convected heat for any rate of fuel consumption is found, approximately, yet so near to that found by M. Peclet's rule, as to make the difference negligible. The constant is (4028) and the following example will make the method plain.

Find the convected heat value when burning 80 lb. of coal per hour per square foot of grate with coal of an estimated heat value of 14,700 B.Th.U. per lb., then the temperature as per table = 2009° F., or 609° F. above the 5 lb. rate and 609 × ·246 = 149·8 units per lb. of gas × 11·7 = 1752·6 units × 80 = 140,212 units, plus (4028 × 80) = 322,240 = 462,452 units of convected heat, taken from (14,700 × 810) = 1,176,000, leaves 713,548 units, or within 1 per cent of that found by M. Peclet's rule.

Therefore the rule is simple and direct, but for excess air a qualified rule must be used to suit a different specific heat.

The following table gives a closely approximate value of the respective heats for increasing rates of fuel.

The conditions are still 14,700 B.Th.U. per 1 lb. of coal and perfect combustion. No excess air, and for the temperatures already determined for increasing rates of fuel by 1 lb. increments.

The following table is based upon values accepted by Clark, and are consistent to the tables he produced with the aid of M. Peclet's formula.

The table as calculated is by the author and is as follows :—

TABLE OF APPROXIMATE RADIANT AND CONVECTED HEAT VALUES IN BRITISH THERMAL UNITS.

*Compiled and Calculated by the Au hor.*

lb. = pounds of coal R = Radiant Heat C = Convected Heat
T = Total

| Lb. of Coal | R Units | C Units | Total Units | Lb. of Coal | R Units | C Units | Total Units |
|---|---|---|---|---|---|---|---|
| 5 | 53,360 | 20,140 | 73,500 | 24 | 237,158 | 115,642 | 352,800 |
| 6 | 63,615 | 24,585 | 88,200 | 25 | 246,319 | 121,181 | 367,500 |
| 7 | 73,876 | 29,024 | 102,900 | 26 | 255,400 | 126,720 | 382,200 |
| 8 | 84,137 | 33,463 | 117,600 | 27 | 264,264 | 132,258 | 396,900 |
| 9 | 94,498 | 37,902 | 132,300 | 28 | 273,803 | 137,797 | 411,600 |
| 10 | 104,659 | 42,341 | 147,000 | 29 | 282,964 | 143,336 | 426,300 |
| 11 | 114,245 | 47,455 | 161,700 | 30 | 292,125 | 148,875 | 441,000 |
| 12 | 123,830 | 52,570 | 176,400 | 31 | 301,286 | 154,414 | 455,700 |
| 13 | 134,416 | 57,684 | 191,100 | 32 | 310,447 | 159,953 | 470,400 |
| 14 | 143,001 | 62,799 | 205,800 | 33 | 319,608 | 165,492 | 485,100 |
| 15 | 152,587 | 67,913 | 220,500 | 34 | 328,769 | 171,031 | 499,800 |
| 16 | 162,172 | 73,028 | 235,200 | 35 | 337,930 | 176,570 | 514,500 |
| 17 | 171,758 | 78,142 | 249,900 | 36 | 347,091 | 182,109 | 529,200 |
| 18 | 181,343 | 83,257 | 264,600 | 37 | 356,253 | 187,647 | 543,900 |
| 19 | 190,929 | 88,371 | 279,300 | 38 | 365,410 | 193,186 | 558,600 |
| 20 | 200,514 | 93,486 | 294,000 | 39 | 374,575 | 198,725 | 573,300 |
| 21 | 209,675 | 99,025 | 308,700 | 40 | 383,736 | 204,264 | 588,000 |
| 22 | 218,836 | 104,564 | 323,400 | 41 | 392,480 | 210,220 | 602,700 |
| 23 | 227,997 | 110,103 | 338,100 | 42 | 401,223 | 216,177 | 617,400 |

| Lb. of Coal | R Units | C Units | Total Units | Lb. of Coal | R Units | C Units | Total Units |
|---|---|---|---|---|---|---|---|
| 43 | 409,967 | 222,133 | 632,100 | 62 | 576,093 | 335,307 | 911,400 |
| 44 | 418,710 | 228,090 | 646,800 | 63 | 584,837 | 341,263 | 926,100 |
| 45 | 427,454 | 234,046 | 661,500 | 64 | 593,580 | 347.220 | 940,500 |
| 46 | 436,197 | 244,003 | 676,200 | 65 | 603,324 | 353,176 | 955,500 |
| 47 | 444,941 | 245,959 | 690,900 | 66 | 611,067 | 359,133 | 970,200 |
| 48 | 453,684 | 251,916 | 705,600 | 67 | 619,811 | 365,089 | 984,900 |
| 49 | 465,428 | 257,872 | 723,300 | 68 | 628,555 | 371,045 | 999,600 |
| 50 | 471,171 | 263,829 | 735,000 | 69 | 637,299 | 377,001 | 1,014,300 |
| 51 | 479,915 | 269,785 | 749,700 | 70 | 646,042 | 382,958 | 1,029,000 |
| 52 | 488,658 | 275,742 | 764,400 | 71 | 654,786 | 388,914 | 1,043,700 |
| 53 | 497,402 | 281,698 | 779,100 | 72 | 663,529 | 394,871 | 1,058,400 |
| 54 | 506,145 | 287,655 | 793,800 | 73 | 672,273 | 400,827 | 1,073,100 |
| 55 | 514,888 | 293,612 | 808,500 | 74 | 681,026 | 406,774 | 1,087,800 |
| 56 | 523,632 | 299,568 | 823,200 | 75 | 689,770 | 412,730 | 1,102,500 |
| 57 | 532,119 | 305,524 | 837,900 | 76 | 698,513 | 418,687 | 1,117,200 |
| 58 | 541,119 | 311,481 | 852,600 | 77 | 707,257 | 424,643 | 1,131,900 |
| 59 | 549,863 | 317,437 | 867,300 | 78 | 716,000 | 430,600 | 1,146,600 |
| 60 | 558,606 | 323,394 | 882,000 | 79 | 724,744 | 436,556 | 1,161,300 |
| 61 | 567,350 | 329,350 | 896,700 | 80 | 733,744 | 442,513 | 1,176,000 |

In the compilation of the above table the deductions are drawn from the data found by MM. Dulong and Petiet, in fact they are obtained by the use of the formula arranged by M. Peclet.

The foundation of the table, for increasing rates of fuel from 5 to 10 lb., is based upon the constant 4028 + 412, which is due to the increasing temperature, making a total of 4440, and the increased constants are

| | | | |
|---|---|---|---|
| From | 5 to 10 lb. | constant | 4440 |
| ,, | 10 to 20 ,, | ,, | 5114·5 |
| ,, | 20 to 40 ,, | ,, | 5538·9 |
| ,, | 40 to 80 ,, | ,, | 5956·5 |

for perfect combustion.

With the aid of the tables it is possible to calculate with some certainty the evaporative capability of any boiler referred to its heating surface.

The tables show the enormous value of radiant and convected heat; besides they indicate how increased temperature reduces the first and increases the second, and the latter always loses some of its value, by heat carried away in the waste gases.

It has already been shown that there is no need for a greater temperature in the chimney than 400° F. for ordinary pressures; therefore anything beyond this proves that some detail is wanting to prevent its increase.

The tables are based on perfect combustion, which may exist when burning 100 lb. of coal per square foot of grate per hour, but when burning 18 lb. per hour probably 50 per cent excess air is needed due to conditional factors. This may be said to be good practice, and, whether an advantage or not, with such consumption and excess air the two heats, radiant and convected, are roughly about equal in value.

*Radiant Heat, Effect, and Distribution.*—There is not the least doubt that radiant heat is given off from the whole of the incandescent fire surface, which includes top, bottom, sides, and ends.

The fire-bar spaces generally average about 25 per cent of the grate area, and one fourth of all the heat due to the quantity of fuel resting on the fire bars is transferred to the ash-pit, and another 5 per cent is lost, due to coal lost as small or dust.

Moreover, the fire gives off heat to the fire door and bridge, which is transferred to atmosphere, and this may easily mean 2½ per cent of all the radiant heat.

Another quantity is lost to the heating surface

above the fire, but not to evaporation, because it is transferred to the heating surface beyond the bridge in boilers of the Lancashire type, and to the front end of the tubes in multitubular boilers, and that amount is estimated as 2·8 per cent of the total radiant heat.

Taking the total of these distributions, and referring it to the estimated heat value of the fuel as lost heat, there is:—

| | | |
|---|---|---|
| 5 | per cent | loss due to small coal and dust. |
| $12\frac{1}{2}$ | „ | downward radiation to the ash-pit. |
| $1\frac{1}{4}$ | „ | lost by fire door and bridge. |
| 5 | „ | due to gaseous heat carried off by chimney. |
| 5 | „ | due to brick settings. |
| $1\frac{1}{4}$ | „ | due to general radiation. |

making a total of 30 per cent of the total estimated heat value of the fuel. Where there are no brick settings 5 per cent is saved, leaving 75 per cent efficiency for no brickwork boilers, and 70 per cent for brick-set boilers.

Thus marine and locomotive boilers should show an efficiency of 75 per cent, and boilers of the Lancashire type 70 per cent.

These may be termed ideal efficiencies.

Efficiencies far below these figures are the general rule—in fact, as a rule they may be 40 per cent below, therefore ample room exists to get a better result.

Probably more than 5 per cent is lost to the brick-set flues. Calling it 10 per cent it still represents an efficiency of 65 per cent, which has been reached with the Galloway type of Lancashire, whilst

75 per cent has been reached by the non-brick type; therefore the supposition of a possible efficiency of 65 and 75 per cent is within reachable limits.

It does not alter the deductions, because some tests have shown better results, and some makers claim an efficiency of 90 per cent. This is not disputed, except to say that it is impossible to ordinary practice.

A general opinion exists that boilers with brickwork flues cause an enormous loss of heat, and under some conditions they do, but under other conditions they do not. That 68 per cent of efficiency has been reached by a brick-set boiler proves that the assumed enormous losses may be due to another cause, or that improper combustion is at fault.

*Furnace-Heating Surface.*—This is limited by conditions, and any idea that a curved surface is better than a flat one of equal surface area should be dissipated. Radiant heat acts in straight lines from the surface it springs from, and from a flat surface to a curved a mean distance is assumed at which radiant heat action is an average. Where a flat plate is placed at the average distance it may be said that one surface will receive as much heat as the other can transmit. The area of action is that of the fire surface, but the shape of the fire, due to thickness of burning fuel, has much to do with radiant heat value. This at once shows the advantage of short over long grates for equal quantities of fuel burnt per hour, which is plainly understood because the fire is thicker and consequently hotter due to the thickness of the body of the fuel, besides the fire is nearer to the furnace heating surface; therefore that is more

efficient which includes a hotter fire for the same quantity of air supplied per lb. of coal. These matters are too important to be dismissed lightly, and will receive more attention at a subsequent period.

By the aid of the heat tables the value of radiant and convected heat is known approximately, and from it the required heating surface can be calculated to give the best result.

These heat values are so important that they need frequent attention, especially in regard to temperature, because a few degrees makes an important difference in the respective heat values, and without the tables it is nearly impossible to ascertain the value anything near to the actual conditions.

Radiant heat declines as the fire temperature increases; therefore when heating surface is to be provided to ensure 35 to 40 per cent of the evaporation for the furnace, and where less work is done by the furnace, it is possible to extend the heating surface dominated by convected heat, whereby a more equable temperature can be arranged for than when radiant heat and convected are about of equal value for a given fuel combustion.

It has already been stated that the determination of the effects of combustion are largely speculative, therefore any analysis must be speculative also, and that gives a reasonable excuse for the following examination.

When burning 10 lb. of coal per square foot of grate which is a very common practice, then B.Th.U. $14{,}700 \times 10 = 147{,}000$ B.Th.U., of which say 104,659 units are radiant, and assuming that 30 per cent is

lost to radiant heat effect, then 73·262 units are useful.

Suppose that 20 per cent of the convected heat is also lost, then 34,673 units are available for useful work, and the two combined represent an efficiency of 73·4 per cent for perfect combustion conditions.

If 50 per cent excess air is admitted the temperature of the fire surface falls 2·5 per cent. Now for equal weights of gas for different temperatures their heat value must be in proportion to their temperatures, or, as 1550 : 1512 : : 42,341 : 41,303 units, but the respective weights of the gases are as 11·7 and 17 lb. per lb. of fuel, and as 11·7 : 17 : : 41303 : 60,013 units of convected heat.

With the total estimated heat value 147,000 − 60,013, that leaves 86,987 units of radiant heat, which is close to the value referred to the result when obtained by M. Peclet's rule.

Referring the new heat values to the same percentage losses as in the other case, and if fully worked out, the efficiency is 74 per cent or 0·6 per cent better than that for the no-excess air performance.

The example is given to show that the furnace is responsible for the chief losses due to combustion.

The admission of excess air reduced the furnace temperature, besides changing the relative values of radiant and convected heat. The difference in the result is small, yet it is sufficient to show that a change of efficiency can be influenced.

The examination can be pushed further with some advantage into speculative analysis, where the difference between the temperatures of combustion with-

out and with excess air is 1600° F., and this divided by ·2377 = 380 units, which means that each lb. of excess air absorbs 380 units of heat, or 2014 units for 5·3 lb., equal the 50 per cent excess air. Thus it is seen that every additional lb. of air admitted reduces the temperature 302° F.

If worked out, neglecting the 1 lb. of combustible and assuming the gas is similar to the air, then 10·7 lb. of gas absorbs 4028 B.Th.U. per lb. of coal, and $4028 \times 5 = 20{,}140$ units. Now, $14{,}700 \times 5 = 73{,}500$ units $- 20{,}140$ leaves 53,360 units of radiant heat which is very close to the result as found by M. Peclet's rule.

The 1 lb. of combustible has still to be considered, and this includes 80 per cent carbon, 5 per cent of hydrogen, 8 per cent of oxygen, and 7 per cent of other gases.

The heat value is found by reference to the C and H, leaving the oxygen and other gases to be neglected, because the estimated heat value only refers to C and H, or 14,700 B.Th.U.

In the case taken 73,500 units are involved, of which 20,140 units are involved in raising the temperature of the air admitted, which includes 62° F. atmospheric temperature.

Whatever the quantity of air admitted, 308 units of the estimated heat value is incorporated by each lb.; therefore be it 1 per cent or 100 per cent excess the factor 308 applied to the total weight quantity per pound of fuel will give the convected heat value. Assuming that 5·3 lb. of air results in reducing the temperature of combustion 1600° F. then $1600 \div 5{\cdot}3 = 301°$ F. per 1 lb. of air admitted, which will

reduce the temperature of combustion in proportion. Therefore air has a direct influence on the maximum concentrated temperature, and must have a similar influence upon fire surface temperature.

Now, given that the temperature for perfect combustion for 5 lb. of coal consumed is 1400° F. and 1366° for 50 per cent excess air which is equal to a difference of 34° F., then $34 \div 5 \cdot 3 = 6 \cdot 4°$ F. per 1 lb. excess. For 120 lb. of coal for perfect combustion the temperature is 2097, and, for 50 per cent excess air, 2030; the difference is 67° F., which, divided by 5·3, gives 12·6 per 1 lb. excess; or practically twice as much, and this demonstrates the fact that an increased quantity of fuel, burnt on an equal grate area, though it increases the temperature of the surface of the fire it also increases the quantitative value of convected heat.

Now, excess fuel cannot be consumed except by increasing the draught, and this means passing more air through the fuel; or through the gases given off by it, and each extra volume of air has to be raised to the critical temperature, and as such temperature increases with the quantity of fuel burnt, more heat is given up to convection, at the expense of radiant heat quantity, and this accounts for what would otherwise be problematic, because the coal only holds so much heat, which may be divided between radiant and convected heat at the discretion of the operator.

Thus, economical combustion lies in the hands of the people who supply the generators, and those who use them.

## CHAPTER XIII.

### THE LESSONS TAUGHT BY EXPERIMENT.

EXPERIMENTAL data have been accumulated from time to time, from which present-day practice has benefited, and untold books have been written which exist to-day, but most expound and explain in accordance with the elevated minds of the writers, making their perusal an almost impossible task to the great majority of men interested in the use of boilers; therefore something more practical is needed to bring necessary knowledge home to thousands who are seeking information to enable them to reach a higher economy in steam boiler practice than is attainable at present.

Perhaps the perusal of experimental performances is most interesting when use is made of them to unravel some problem whose solution will aid future economists.

Radiant heat acts quite independently, and has no influence upon any substance of a gaseous nature any more than it has upon the atmosphere it penetrates, as sun's rays, in its passage to the earth.

It is well known as a scientific fact that when heat is projected on to a cold surface, it will reflect heat back upon another surface; the rays will fire any substance that will inflame, showing that the

atmosphere offers no resistance to the action of rays of heat.

It is quite possible to concentrate heat by reflection. Advantage of this is taken in fusing metals, especially in the old style of metallurgical furnace, where heat is reflected back from an arched roof to the fire, until the temperature is raised to over 5000° F.

These are known principles on which rest other applications not so certain, but the heat transmissions in boiler practice are principally due to conduction which depends upon the difference between the temperatures of the side of a plate which receives the heat, and the opposite side which disperses it; therefore the greater the difference so is the transmission assumed to be the more active.

In the practical work of experiment Robert Stephenson sought to determine the heat effect produced by different surfaces, and found that 6 square feet of direct heating surface under radiant heat was more valuable than 36 square feet under convected heat, which is six times faster for radiant heat.

Mr. C. W. Williams, to whom the world is indebted for a very courageous attempt to lay bare the various chemical effects resulting from combustion of fuel, though perhaps many disagreed with his conclusions, called attention to matters that had hitherto received scant notice, and gave an impetus to investigation.

He differentiated the value of convected heat when acting upon surfaces near and remote from the source of supply, with an apparatus in which

the first section was 6 inches long, and four other sections 12 inches long.

He used a tube 3 inches diameter through which the gases moved, and the heat was common to the five sections.

The firing method was a jet of gas, arranged so that no radiant heat could influence the result.

A sketch of the assumed apparatus is given below.

The amount of water evaporated by the five sections were,

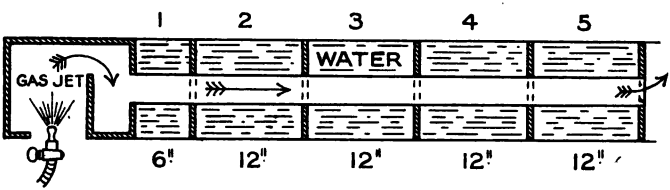



FIG. 16.

| | | | | |
|---|---|---|---|---|
| Nos. 1 | 2 | 3 | 4 | 5 |
| 6 lb. | 2·56 lb. | 1·5 lb. | 1·2 lb. | 1 lb. |

Making a total of 12·26 lb., showing that the first 6 inches were equal to all the others. Probably, radiant heat by conduction had an influence upon the first section, therefore the Stephenson test was qualified by that found by Williams, assuming that conducted radiant heat had an influence on the first section.

Others tried the value of surfaces placed at right angles to the line of movement of the gases, and the accuracy of these early experiments is borne out by what present practice teaches.

No limit rate of transmission of heat through plates

has been determined, and opinions are diverse even to-day.

The question of the effect of thickness of plate is still a doubtful factor, though there is every reason to assume that thickness may have, and must have, an influence upon the time before active transmission commences; but when the transmitting plate has attained the reigning temperature, there seems little reason to doubt that heat will traverse an element in a given time almost irrespective of thickness. In practice, thickness is determined by the pressures required.

Thickness must increase the time taken to raise a plate to a given temperature, but, when this temperature is attained the rate of transmission appears to be governed by the rate at which water can receive heat, and not by the transmitting thickness of the plate.

Craddock's simple experiment goes far to support the contention. His experiments were carried out with a tube filled with hot water at 180° F., and he found that after 25 minutes' exposure to still air it lost 80° F., but when moved through the air at 58·6 feet per second it lost 80° F. in 2·04 seconds. Another experiment with the tube immersed in water was made when it lost 80° F. in 1 minute, whilst 80° F. was abstracted in 30 seconds in water flowing at 2·93 feet per second.

In still air the tube was in contact over all its surface, whereas when moved at 58·6 feet per second only half of the surface could be in air contact, the other side being under a negative pressure. Between the still air condition and the other, the first time being taken as 12, the latter is 1.

Brownlee, when testing the outflow of steam through a given orifice, found that when the outside pressure was 58 per cent of the delivering pressure the outflow was maximum, and was neither accelerated nor retarded even down to a perfect vacuum. Presumedly the law refers to all pressures for gaseous substances.

He ascertained that the velocities of efflux at constant density increased very slowly between 25·37 and 100 lb. per square inch absolute pressures when discharging into atmosphere, because the range was between 863 and 898 feet per second.

The quantity of steam discharged under a driving pressure of 25·37 lb. was 10·1 per cent less than 25·37 lb. (referred to weight), and at 100 lb. it was 13·7 per cent, or a difference of 3·7 per cent. Taking the velocities as a percentage of the greatest velocity the difference is 3·9 per cent, which shows the consistency of the law of 58 per cent.

For the sake of argument, say that 58·6 feet is the velocity at which a mass is moving, then 58 per cent equal 34 feet per second, equal to a difference of 24·6 feet: so when one body is moving at 58·6 feet per second it is presumedly met by another body moving at 34 feet per second.

In Craddock's first experiment, in still air, the whole surface of the tube is embraced by the medium, and heat was abstracted by one layer of air transmitting heat to another until the whole 80° F. was got rid of. The rate was 80° F. in 25 minutes and the transference was slow.

In the second case the air movement was 24·6 feet per second faster than the other, and 80° F. was abstracted in 2·08 minutes.

It is obvious that the rate of abstraction was due to the quantity of air passing the tube.

Now, 24·6 referred to cubic feet and velocity, will carry away heat 24·6 times as fast as 1 cubic foot of air can transmit it through 24·6 cubic feet of air, even if the whole surface of the tube was dominated by the air current, but only half of the tube was affected, therefore the rate was 12 to 1, or 80° F. was abstracted in 2·08 minutes.

Given that the cross-sectional area of the tube is 1 square foot, then 24·6 feet × 60 seconds × 2·08 minutes = 3070 cubic feet of air which must pass the tube in the time, therefore 80° F. is referred to 3070 cubic feet or = ·026° F. per cubic foot.

Supposing 1 lb. of air equal 12·8 cubic feet, then ·026 × 12·8 = ·3328 units per lb. of air, whose specific heat is ·2377, and ·3328 × ·2377 = ·079° F. of heat is carried away per cubic foot of air.

Now, 3070 ÷ 12·8 = 239 lb. of air, and 239 × ·079 = 18·8 units carried away in 2·08 minutes, and 18·8 ÷ ·2377 = practically 80° F.

Probably the total area of the tube was about 4·7 square feet, but assuming the curved surface was only equivalent to the effect produced by the cross-sectional area and referred to 18·8 units for 2 sides, or 9·4 units per square foot of surface area per side in 2·08 minutes = 4·5 units per square foot per minute.

No measurements are given for Craddock's apparatus, but it may be assumed that he would experiment with the usual unit dimension of 1 square foot of sectional area.

Assuming the temperature of the atmosphere was

60° F. the difference, or 180° F. − 60° F. = 120° F., and assuming that 80° F. equal 80 units of heat, abstracted in 25 minutes = 3·2 units per minute × 60 minutes ÷ 120 = 1·6 units per degree of difference per square foot per hour for the still air condition. The reference is made on the assumption that only 1 square foot of surface was affected, but if it was on both sides then 3·2 ÷ 2 = 1·6 units, then for 2 square feet it is 3·2 units, hence the proportion gives equality.

In a similar way 4·5 units per square foot were abstracted in moving air, but the negative effect supplemented the positive by an equal effect and amount making the actual abstraction 9 units per square foot, and 9 × 60 ÷ 120 = 4·5 units per degree of difference per square foot per hour.

Mr. Brownlee's 58 per cent law is the basis of the deductive values, and its accuracy is borne out by the result attained approximately.

**Craddock's experiment,** and the deduction drawn from it, is qualified by what others found by experiment, because M. Peclet found that heat was dispersed through sheet iron to air at the rate of 1·6 units per square foot per hour per degree of difference, and the rate was maintained irrespective of the kind of heat, whether gas or water, the receiving medium in all cases being still air.

In fact it defined a rate at which air is capable of conveying heat, or rather its conductivity.

Fox, Head & Co. of Middlesborough found by direct experiment that 1·25 lb. of 50 lb. pressure steam was condensed per square foot per hour, or equal to 4·79 units per degree of difference between

the inside and outside temperatures, but this was carried out in the open air with a moving current. Yet when the same boiler was enclosed within a room the rate of dispersion was only one-third of that found in the open air, or about 1·6 units for the conditions of surface, time, and difference; therefore these experiments set a rate with which Craddock's experiments tally so closely with that of M. Peclet's, that the rates given are fully substantiated. The rates may be taken as 1·6 units for still air and 4·8 units for moving air, and these form a basis for computing both transmissions and dispersions, because they are founded on three separate experiments which compare very nearly as to result.

The method adopted to prove the value of Craddock's experiment is simple, direct, and reasonable, but it is not intended to upset any principle or a more scientific deduction, though the intention is to make the method plain to the lay mind.

With these examples furnace conditions may be examined, and physical facts are demonstrated by what practice teaches, and, whatever the fuel, air is required for its combustion, and to aid further analysis the average volume of 1 lb. of air is taken as 12·5 cubic ft., and that 10·7 lb. of such air is required for 1 lb. of coal of the estimated heat value of 14,700 B.Th.U. Its constituent elements are assumed to be carbon, 80 per cent, hydrogen 5 per cent, oxygen, 8 per cent, other gases, 7 per cent, but the latter are left out of consideration. These values have been given before, but are repeated here to form the basis of further examination.

Now, 1 lb. of hydrogen requires 8 lb. of oxygen,

contained in 34 lb. of atmospheric air, and after combustion there are 9 lb. of steam and 26·8 lb. of nitrogen. Carbon requires 2·66 lb. of oxygen which is contained in 11·6 lb. of air, and the products are 3·66 lb. of carbon dioxide and 8·94 lb. of nitrogen, therefore 1 lb. of coal requires, for 5 per cent of hydrogen, 1·74 lb. of air, and 80 per cent of carbon requires 9·28 lb. equal to a total of 11·02 lb. of atmospheric air, but the 8 per cent of oxygen must be considered as being equivalent to ·348 lb. of air, and 11·02 – ·348 = 10·67 lb. of air required, or say, 10·7 lb. per lb. of coal. As already stated the products after combustion equal ·45 lb. of gaseous steam, 2·94 lb. of carbon dioxide, and 8·31 lb. of nitrogen.

These gases have varying capacities for heat, and are referred to the standard of water, because water of all fluid substances has the greatest capacity for heat.

As a ready reference a few substances and their specific heats are as follows :—

The specific heat of air = ·2377
steam = ·475 (Also Clark's gaseous steam.)
carbon-dioxide = ·2164
oxygen = ·2182
nitrogen = ·244
hydrogen = 3·4046 (Clark's value from his tables at constant pressure.)

Generally, the products of combustion are referred to an average specific heat, obtained as already explained.

With these various properties and values, users of steam boilers wish to know the limit of useful

work they can obtain from an estimated fuel energy.

The chief object in burning fuel in a boiler furnace is to make steam, and the next to produce it economically, and thirdly to evaporate the greatest quantity of water with the plant which costs the least to instal, the least for upkeep and purchasing cost.

*Work done by the gases behind the bridge.* Burning 216 lb. of coal with 50 per cent excess air means 3456 lb. of air, and allowing 13 cubic feet per lb. about 44,928 cubic feet is required, and this means about 12·4 cubic feet to enter the furnace per second.

Assuming the gas volume to be the same as the air, for equal weights the respective volumes are as their absolute temperatures. With a chimney temperature of 400° F. the 12·4 cubic feet becomes 20·4.

Suppose the chimney is 50 feet high and the discharge is effected by different weights of equal columns of gas and air. The relative volumes for 400° F. and 62° F. are 50 and 30, and their weights for equal volumes, referred to the weight of a cubic foot of air at 62° F. = ·08, and 50 × ·08 = 4, and 30 × ·08 = 2·4; or a difference of 1·6 lb. for equal columns at different temperatures.

The discharge velocity is 8 times the square root of the height, or $8\sqrt{h} = 45{\cdot}6$ feet per second by 1 square foot of discharge area. As 2·4 : 1 : : 50 : 20·8 cubic feet per lb. at 400° F. and 45·6 ÷ 20·8 = 2·2 lb. the theoretical discharge per second, and 2·2 × 60 seconds × 60 minutes = 7920 lb. per hour. As each lb. of fuel produces 17 lb. of gas, so 216 gives

3672 lb. or less than half of the theoretical quantity, therefore natural draught is ample for the quantity assumed.

Referring the conclusions to a Cornish boiler 6 feet diameter, by 18 feet long, where fire-grate and dead plate take up 7 feet of the length. Generally, only two-thirds of the surface of the circular tube is deemed efficient. The two wing flues are high and narrow, though only that part due to the boiler side is useful for evaporation, and the top of the bottom of the return flue. When traversing the flues the gases lose heat, volume, and velocity, which latter is governed by the rate of discharge from the chimney mouth, that sets the velocity for the air entering the fire and for the gases discharged from the flues. Immediately the gaseous volume settles itself behind the bridge its temperature is high, but it loses heat to the enclosing walls, and is subject to the compression effect produced by the weight of the chimney gases on the unit area.

A rough method of computing the efficiency of a Cornish boiler of the kind previously referred to is as follows:—

With a furnace temperature of 1550° F. and a steam temperature of 328° F. the difference is 1222° F. for the starting condition and $400 - 328 = 72°$ F. for the finishing or $\frac{1222 + 72}{2} = 647°$ F. the average difference.

Suppose 4·8 units per degree of difference per square foot per hour is the average rate of heat transmission for a moving gas effect, then 4·8 × 647° F. × 294 square feet of heating surface beyond the

bridge = 913,046 units, and accepting the view that the furnace supplies 50 per cent of the evaporation, then twice 913,046 = 1,826,092 units, will give the whole boiler performance, whilst the estimated heat value for 216 lb. of coal is 3,175,200, therefore 57 per cent efficiency may be taken as the maximum.

Taking another view, supposing the velocity of the gases behind the bridge is 7·8 feet per second, the final velocity is only about 3 feet due to 20·4 cubic feet of gaseous product. If 17 lb. of gaseous product requires 4·131 units, already calculated to raise the temperature of the gases referred to 1 lb. of coal, then 4·131 × 216 = 892·2 units × (1222 − 62 = ) 1160 = 1,034,952 units for convected heat, but 5 per cent of this never existed because of small coal loss, besides another 5 per cent is lost by general radiation. Therefore, the assumed efficiency before determined is qualified, or 57 per cent is the efficiency. There is no question as to the possibility of reaching this efficiency, and it should be possible without any more than ordinary care and attention.

It is an advantage to know the value of various heating surfaces, and that is determined by speculative analysis.

The 11 feet of circular flue behind the bridge accounts for 103·4 square feet, the two wing flues for 136·6, and the return flue for 54 square feet, therefore the 294 square feet is accounted for. These surfaces are not all of equal value but they may be referred in respect of length to one diameter, and reduced in length by their assumed non-efficiency, or the actual length may be taken and its efficiency value recognized.

The first length is only two-thirds efficient, and

two-thirds of 11 = 7·32 feet, or its actual length referred to ·66 gives an equal value.

But the simplest method is to give a relative length as efficient as follows :—

| | | |
|---|---|---|
| 1st section | 7·2 | feet |
| 2nd „ | 7·2 | „ |
| 3rd „ | 4·8 | „ |

based on the assumed efficiencies for the actual lengths as ·66, ·4, and ·3.

The total efficient length equals 19·2 feet, all of which is efficient, and each section is referred to a mean temperature, the average between 1550 and 400 = 1150° F. divided by 19·2 = nearly 60° F. per foot run. The resulting values are as follows :—

1st section, 7·2 × 60 = 432° F. taken from 1550 leaves 1118° F., the final at the end of the section, and

$$\frac{1550 + 1118}{2} = 1334° \text{ F. mean temperature.}$$

2nd section, 7·2 × 60 = 432 taken from 1118 leaves 686° F. the final at the end of the section, and

$$\frac{1118 + 686}{2} = 902° \text{ F. mean temperature.}$$

3rd section, 4·8 × 60 = 288 taken from 686 leaves 398° F. the final at the end of the section, and

$$\frac{686 + 398}{2} = 542° \text{ F. mean temperature.}$$

Now, the value of each section =

No. 1 = 7·2 × 1334 = 9604·8
„ 2 = 7·2 × 902 = 6494·4
„ 3 = 4·8 × 542 = 2601·0

making a total of 18,700·2 and the available units, say 913,046 ÷ 18,700 = say 49 which is the value of a unit of the factor, therefore the factor for each

section multiplied by the unit value gives the B.Th.U. valuation, or—

| | | | | |
|---|---|---|---|---|
| 1st section, | 9604·8 | × 49 = | 470,635 | B.Th.U. |
| 2nd ,, | 6494·4 | × 49 = | 316,115 | ,, |
| 3rd ,, | 2601 | × 49 = | 127,449 | ,, |

= 914,199 B.Th.U. which is near enough, because if fully worked out the available heat units would be accounted for.

Taking the various flue efficiencies as percentages of the complete efficiency value, the first section or flue behind the bridge = 51·8 per cent, wing flues 34·3 per cent, and bottom flue 14·2 per cent. It is quite evident that these percentages will stand good for any quantity of convected heat.

The 913,046 units of convected heat is about 70 per cent of the estimated total value, and add to this say 3·1 per cent for transferred radiant heat, therefore 30 per cent of convected heat is lost, plus the 3·1 per cent = 33·1 per cent of the total, credited to operation behind the bridge. These values refer to any amount of convected heat, and the per cent proportions will remain true for either maximum or minimum efficiencies.

For the present case 913,046 units refer to 70 per cent of the total convected heat, therefore 30 per cent has to be accounted for, but 3·1 per cent of the total heat value is due to radiant heat. There can be no question of the presence of extra heat at the commencement of the evaporation effects just beyond the bridge, because every experiment proves the value of the early part of Lancashire fire-tube beyond the bridge, and the early portion of the tubes in a multitubular boiler. More than that, it is equally

evident when water is boiled in an open boiler under atmospheric conditions.

This heavy ebullition reaches 3 feet behind the bridge, and it is fair to assume that fully 9 square feet of the top surface behind the bridge is under the influence of radiant heat effect, both direct and by conduction.

Now, an average of 10 units per degree of difference will easily be transferred, and $1550 - 328 = 1222 \times 10 \times 9 = 109{,}980$ units, call it 100,000, which is practically 3·1 per cent of the estimated heat. Thus the deduction is reasonable and closely approximate to what practice teaches.

Probably the actual temperature at the end of the flue tube as given is greater, but not when referred to the entrance to the wing flues. Heat is certainly lost to the mass of brickwork forming the wing flues, dry back, and bottom flue.

The dry back easily means 86 square feet of brick surface exposed to the heat of the gases, and the wing flues present 220 square feet, whilst the bottom flue may account for another 126 square feet making a total of 432 square feet, or $1\frac{1}{2}$ times as much as the actual heating surface in contact with water.

Even the best laid brickwork about a boiler is sensibly hot to the hand, and 180° F. may indicate its temperature, whilst the temperature of the boiler house may be 80° F. as an average. The difference is 100° F., then $100 \times 4{\cdot}8$ units (already defined) $\times$ 432 square feet = 207,360 units lost by the brickwork. Referred to convected heat value this loss equals nearly 23 per cent, but to the estimated heat value of the fuel fully 6 per cent. The

waste gases account for fully 9 per cent, say 10 per cent.

With these deductions a balance sheet of the various distributions of the total estimated heat value becomes possible.

For 216 lb. of coal the estimated heat = 3,175,200 B.Th.U., and the radiant and convected heat values closely approximate the values obtained by M. Peclet's rule.

Temperature 1550° F., excess air 50 per cent, rate, 12 lb. per square foot of grate, steam temperature 328° F.

Radiant heat = 1,870,849 B.Th.U.
Convected " = 1,304,351 "

equal 3,175,200 units.

*Balance Sheet.*

| | | | | |
|---|---|---|---|---|
| 5 | per cent | small coal and dust losses | = 158,760 | B.Th.U. |
| 14 | " " | lost radiant heat by fire-bar spaces | = 444,528 | " |
| 3 | " " | by fire ends | = 95,256 | " |
| 6 | " " | brickwork | = 190,512 | " |
| 10 | " " | waste gases | = 317,520 | " |
| 2 | " " | by general radiation | = 63,504 | " |
| 2 | " " | CO. carried away in waste gases | = 63,504 | " |

or equal to the estimated value correctly worked out.

Thus, 42 per cent of the estimated heat is lost, and 58 per cent is referred to evaporative efficiency.

The first loss by care and attention, at least, can be reduced, say, to 2 per cent.

The second may be reduced by using shorter grates and thicker fires, and extended experiment shows that a saving of at least 2 per cent is possible.

The third may be slightly increased by using thicker fires, but this has been considered when the 2 per cent advantage is stated.

The fourth can probably be reduced to 3 per cent by careful clothing and by fire-brick linings.

The fifth cannot be reduced much, though probably 1 per cent may be saved by efficiently covering all exposed parts with non-conducting material, and the sixth can be reduced 1 per cent by careful attention to the fire. As a general assertion fully 10 per cent of increased efficiency is possible, or a Cornish boiler should be able to give an efficiency of 68 per cent. Supposing this is too near the ideal, it is still possible to get an efficiency much better than usual practice gives. And that will represent an enormous saving over all the Cornish boiler plants in existence.

The Lancashire type of boiler, whilst giving a larger quantitative efficiency, also shows an increased fuel efficiency, but that may be attributed to an apparently decreased slippage of heat by brickwork, whereas it is primarily due to an increased evaporative surface for a relatively smaller brickwork surface.

Fortunately very authoritative trials have been carried out with such boilers, and one of these will be taken as an object lesson in boiler economy.

## CHAPTER XIV.

### PHILADELPHIAN EXHIBITION TESTS.

During the Philadelphian exhibition authoritative tests were made with various boilers, and amongst them was a Galloway boiler of the Lancashire type. Though these tests were made as far back as 1876 nothing better has been attained since.

The dimensions given by the makers were qualified by Mr. D. K. Clark, and were as follows:—

The boiler was made of steel 28 feet long by 7 feet diameter fitted with two furnace tubes of 2·75 feet diameter, 7·5 feet long, joined at the back to one elliptical flue, carried the full length of the boiler, and crossed by thirty conical water tubes placed vertically.

The gases generated in the furnaces passed over the bridges into the elliptical flue, and zig-zagged through the nest of tubes, then they were divided at the end, between the two wing flues, and through them to the front, and joined at the end to pass down into the bottom flue, then back to the end of the boiler to the foot of the chimney.

With a total heating surface of 852·54 square feet, of which 139 square feet is referred to furnace heating surface, and 713·54 square feet for other surfaces beyond the bridges. Steam pressure 70 lb.

per square inch above atmosphere, waste gases 383° F., feed water 54° F., and the estimated heat value of the fuel 14,700 B.Th.U. (this was not given, but it was bituminous coal of good average quality).

Excess air 50 per cent. Coals burnt per square foot 11·4 lb. or 410·7 lb. on 36 square feet of grate area.

The quantity of water evaporated per hour equal 58 cubic feet. It is noted that the official report says "apparently evaporated". Though this implies some doubt, still the quantity works out at 8·77 lb. of water per lb. of fuel, or from and at 212° F. 10·4 lb. as

$$\frac{(1177{\cdot}9 + 32) - 54}{966} = 1{\cdot}196 \times 8{\cdot}77 = 10{\cdot}4 \text{ lb. per}$$

lb. of coal.

Taking the temperature of the fire surface as 1550° F., radiant heat equal 3,509,009 units, and convected 2,524,539 units, equal to a total of 6,033,648 B.Th.U. being, approximately, the estimated value of the fuel.

The gaseous products require 4·131 units to raise the temperature 1° F.; then 1550 – 62, leaves 1488° F. × 4·131 × 410·7 = 2,524,531 units, practically that found by M. Peclet's rule.

The heat carried away in the waste gases = 388 – 62 = 321° F. × 4·131 × 410·7 = 544,608 units.

Now, the difference between the initial and final temperatures of the gaseous products = 1550 – 383 = 1167° F., and 1167 × 4·131 × 410·7 = 1,879,932 units of convected heat must have been absorbed during their passage from the bridge to the entrance to chimney; therefore 99,991 units have to be ac-

counted for, but the temperature may have been more than 383° F., or CO was carried away equal to the difference as heat units unconsumed.

The total heat per lb. of steam at a pressure of 85 lb. per square inch (abs.) = 1177·9 units but the feed was 54° F. and 1177·9 − (54 − 32) = 1155·9 units per lb. and 8·77 lb. × 1155·9 × 410·7 = 4,163,320 units, and as 6,033,648 : 100 : : 4,163,320 : 69 per cent, the assumed claimed efficiency.

Supposing radiant heat gave sufficient effect to the flue behind the bridge to compensate for heat lost by the brickwork, then 1,879,932 units is referred to evaporation, and as 6,033,641 : 1,879,932 : : 100 : 31 per cent, leaving 38 per cent for radiant heat to account for 38 per cent of the evaporation ; or stated in another way, if convected heat accounted for 44·9 per cent of the evaporation radiant heat must account for 55·1 per cent. This is a most abnormal result, and probably this was the reason why the note of "apparent evaporation" was appended to the official report.

Assuming that the whole of the products of combustion are accounted for, and 31 per cent of the efficiency was credited to them, the remaining 38 per cent is concerned in the radiant heat effect.

Probably the usual 5 per cent loss due to small coal and dust was avoided by returning all combustible ash to the fire.

This must have been the case because all convected heat is accounted for ; therefore the remaining value must be due to the radiant heat effect. With the relatively thin fire 25 per cent of the heat must have been lost by the fire-bar spaces ; but on the other hand

returning the hot ashes to the fires would restore some of it to useful work; how much is hard to say, still it is possible. Anyway it would confine the loss to actual radiant heat, and not to lost fuel.

As the Pennsylvania trials were important it is certain that all exposed surfaces would be efficiently covered with non-conducting material, including all brickwork, and the care exercised in stoking would reduce the CO losses.

Supposing 5 per cent of small coal loss was saved, and
5 per cent by efficient clothing of exposed parts
1 per cent saved in CO, and
8 per cent is credited to the flue evaporation, then,

where the previous examination of a Cornish boiler only considered 3·1 per cent as credit for radiant heat to flue purposes—the difference, 4·9 per cent, is in favour of the present performance, or 15·9 per cent was saved out of a loss of 42 per cent, and under the 42 per cent loss the efficiency was 58 per cent as assumed, then 42 – 15·9 leaves 26·1 per cent equal to a putative efficiency of 73·9 per cent, but only 69 per cent was claimed. The difference of 4·9 per cent may easily be accounted for by assuming that the actual saving was less than 15·9 per cent; besides the feed water for the Cornish example was taken at 62° F. whereas the Philadelphia feed was 54° F.

Taking the efficiencies as proportionate to the feed temperatures, then as 62 : 54 : : 73·9 : 66 per cent. Two factors of advantage may easily account for the 3 per cent. The saving could easily be more than

that assumed, because the conditions were favourable to it, and the estimated heat value of the fuel may have been less than 14,700 B.Th.U. per pound of coal.

Whatever view may be taken, the trial was one the firm could be proud of, because it has not been exceeded or even equalled at this date.

A balance sheet of the heat distributions are as under:—

| | | Per Cent | Per Cent | Per Cent |
|---|---|---|---|---|
| Efficiency referred to furnaces | = | 37·8 | | |
| „ „ back flue | = | 17·0 | | |
| „ „ wing flues | = | 6·1 | | |
| „ „ bottom | = | 4·6 | | |
| „ „ cone tubes | = | 3·5 | = 69 | |
| Losses, Waste gases, probably | = | 12 | | |
| „ Brickwork | = | 14 | | |
| „ Radiation | = | 2·5 | | |
| „ Heating water from 54° to 62° F. | = | ·4 | | |
| „ CO carried off | = | 2·1 | = 31 | = 100 |

It is quite probable that an even better result might have been reached by shortening the grate and using a thicker fire to burn the same weight of coal. This matter of thin and thick fires is worth more than a little attention: for instance, for a grate 6 feet long by 3 feet wide = 18 square feet the bar spaces may equal 6 square feet.

Suppose 3 inches and 12 inches are the extreme limits of fire thickness; the first represents an area of 40·5 square feet of fire surface and the other 54 square feet. As a percentage the space to the full

area for the thin fire is 14·8 per cent and 11·1 per cent for the thick fire, showing a reduction of 3·7 per cent; but the ends of the fire radiate heat, so the gain by the thick fire for downward loss is 3·7 per cent, but the loss from the ends is 11·1 per cent. As these equally apply to reduction of heat and dimension, the losses are as follows by analogy:—

Thin fire 14·8 + 3·7 loss = 18·5 per cent.

Thick „ 11·1 + 11·1 „ = 22·2 per cent, showing that the thick fire loses more heat than the thin one proportionately; therefore the saving proved by test cannot be due merely to the difference in thickness,

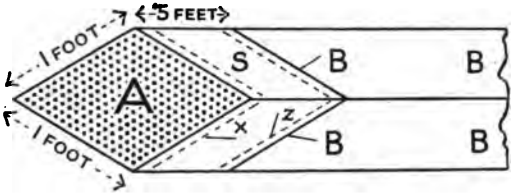



Fig. 17.

but the thick fire is closer to the heating surface, and is also hotter than the thin one, thus radiant heat is more active to produce a greater evaporation.

In spite of the high efficiency of the Galloway boiler the fact remains that a large amount of heat is wasted. In this connexion it is well to demonstrate practically how heat is transferred from the surface of the fire to a surface opposed or adjacent to it, and the following diagram will aid the intention.

Fig. 17 is supposed to represent 1 square foot of grate area; viewed from below the fire is supposed to be on the X side of A, the plate in

which are the perforations, assumed to equal one fourth of the area, which perforations represent the fire-bar spaces. The Z side of plate B is the outside or furnace side of the flue plate, and B is the water side of the plate. The space between the surface of the fire and the surface Z is assumed to be 6 inches across, and the X face is supposed to be kept at a constant temperature of 1550° F.

On looking at the sketch it is quite evident that the fire overhanging the spaces must radiate heat downward into the ash-pit, then to the open air, where it is lost.

Suppose 49 B.Th.U. are given off X face every second, part of it being radiant, and the other part associates itself with the gases evolved from the fuel to increase their temperature which is the average of the contents above the fire.

Suppose this 49 units are contained in a given weight of fuel of which ·00338 lb. are required to keep up the temperature of 1550° F. in which is included ·05666 lb. of excess air, the average specific heat of the gaseous product being ·243, and $\cdot 05666 \times \cdot 243 \times (1550 - 62) = 20 \cdot 8$ units allocated to the gas, leaving 28·52 units as radiant heat. The space dimension above the fire is half of a cubic foot at 62° F., but heating the volume through 1488° F. raises the volume to 1·85 cubic feet, and assuming the gas to be the same as the air, then 1·85 cubic feet of gas is at the same temperature as the fire surface. The gas has taken in all the heat it can hold, or rather all the heat available, because radiant heat has no effect upon its volume. But radiant heat as determined by Stephenson and others is six times

as active as convected, therefore, the gaseous heat can have no influence on surface Z. As the assumed 28·52 units of radiant heat are supplied each second, the same amount must be got rid of in an equal time. It is necessary to compare the relative effects of radiant and convected heat when evolved from one source though independent of each other. Distance affects the value of radiant heat, the effect decreasing as the square of the distance, and at 38 feet away the square is equal to 1444, and when the receiving surface is 62° F. at the distance radiant heat has no active effect on the surface, though it emanates from a source of 1550° F.

Assuming that this is referred to the rule of $8\sqrt{38}$, the result is 48·8 feet per second; this supplies as an argument, velocity to compare the movement of the gases over the fire surface and heating surface with.

Where radiant heat is in excess of what the plate surface will absorb, it is either reflected back or carried away by conductivity. Part is certainly lost from the fire ends, and a large part by downward radiation from the fuel overhanging the fire-bar spaces. Call this loss 25 per cent of 28·52 = 7·13 units lost, which leaves 21·37 units to act above the grate, and 21·37 × 3600 seconds × 18 square feet = 1,384,776 units of radiant heat. Probably 5 per cent was lost by small coal and dust, and say 7 per cent to the surface beyond the bridge, and probably 8 per cent from the fire ends by door and bridge; thus 20 per cent of the calculated amount is not useful, therefore the total radiant heat engaged in evaporating by furnace surface equal 1,107,821 units.

The Pennsylvania trial assumed an estimated heat value of 6,033,648 units based on 14,700 units per lb. of fuel, but this was found to be too high by nearly 5 per cent. To be exact the difference was 4·9 per cent, and 4·9 per cent of 6,033,648 = 295,648, leaving 5,738,000 units of estimated heat.

The furnace evaporation was credited with absorbing 37·8 per cent of the estimated heat, or 2,168,564 units, but 1,107,821 units refers to 1 furnace, × 2 = 2,215,642 units, thus, if correctly worked out the present estimate is equal to the assumed actual performance. Thus the analytical example shows that the deduction is borne out by what practice teaches.

Some attention is needed in regard to the effect of thickness of plate between the fire on one side and water on the other, also the effect of closeness of fire to it, because it was previously shown that the thick fire really lost more heat, relatively, than a thin one, in spite of the fact that innumerable tests always showed a marked saving for the thick fire. With the usual cylindrical furnace with the top 12 inches above the surface of the fire, it is arbitrarily assumed to represent an average of 6 inches above for a presumedly flat surface, and as an equally arbitrary deduction, suppose at 6 inches 75 per cent of the heat referred to the fire surface is received at 6 inches away. Suppose a thinner fire assumes a distance of 7½ inches from the surface. As a determined factor for convenience, suppose that every inch away from the surface loses ·0417 per cent of the source value, then 1·5 × ·0417 per cent = say, ·06 per cent less radiant heat value is received by the plate. Now, doubling the quantity of fuel burnt

on an equal grate area increases the temperature, say, for 10 to 20 lb. 10 per cent, and suppose the double quantity makes the difference in thickness named, the $10 + \cdot 06 = 10{\cdot}06$ per cent in favour of the thick fire for radiant heat effect, but the gaseous products are correspondingly hotter also.

Suppose 10 per cent is the actual gain, and allowing that the thick fire loses 5 per cent more radiant heat than the thin one, there is still 5 per cent in favour of the thick fire, and experiment proves it. But something else occurs, because the unit weight of the gas per lb. of fuel is less for the thick fire than the thin one, due to less air being required for combustion, yet the hotter gas for a less weight may be of equal volume to the other, but the double volume of gas for the double furnace sets up a higher velocity in the side and bottom flues and that means a higher chimney temperature, but any evil effects may be mitigated by curtailing the outlet area from the flues, thus putting the gases under considerable compression, which will add much to evaporative efficiency and lose nothing in economy.

Returning to the diagram sketch, it is evident that the heat given to B must be got rid of or the temperature would rise until the metal was fused. This brings in a very doubtful factor, i.e. the temperature of the plate surface next the furnace.

*Note.*—A thin plate, according to the general belief, transmits heat faster than a thick one, therefore the half-inch plates should transmit heat four times faster than one-inch plates.

Where radiant and convected heat exist separately at 1550° F. it is reasonable to say that the tempera-

ture of source or heart of the fire must be 3100° F., and with an average temperature of 1550° F. there must be a film of low temperature at the plate. Dr. Nicolson speaks of such a film, but it cannot be colder than the plate it is in contact with, and that is certainly higher than the heat of the substance held inside of the boiler.

*Laws of Heat Transmission and Deductions from them.*—The law asserts that heat flows across a plate in proportion to the difference of temperature of its two sides and inversely as its thickness.

Rankine and Peclet's rule $= Q = K\dfrac{T - t}{e}$ B.Th.U.; where Q is the quantity of heat, T and $t$ the temperature on the two sides (° F), $e$ thickness of plate in inches and K the thermal conductivity. K varies in value, for wrought iron it is 450; mild steel, 450; cast iron, 324. Such a rule gives an impracticable rate and is shown as follows: Let T = 1500 and $t$ 324; then for a plate 1 inch thick

$$Q = 450 \; \frac{1500 \; - 324}{1} = 450 \times 1176 = 529{,}200$$

units.

Applying the same rule to a half-inch plate for equal conditions $Q = 450 \; \dfrac{1500 - 324}{\cdot 5^2} = 2{,}116{,}800$ units, or four times the previous value.

The formula of Rankine and Peclet which is mostly used is $Q = \left(\dfrac{T - t}{200}\right)^2$, 200 being a co-efficient, and the result is units per degree of difference. The rule ignores thickness of plate, which appears to be reasonable, because the contention is that any thick-

ness, when raised to the critical temperature, will transmit heat to a substance at the rate of the difference between the giving and receiving temperatures. A thick plate will take longer to heat up than a thin one, but the same amount of heat will be given off a given surface where the temperature is the same.

The general impression is that the surface of a plate in contact with water must be hotter than the water; but it may not be more than 10°, or if the water is 328° the plate surface is 338° F.

The outside of the plate, being that on which the transmitting heat impinges, does not appear to be influenced by thickness; yet another 10° is added making it 348° F. This is quite reasonable because radiant heat supplies the means for giving temperature to the substance and the plate must receive and pass it on, which it cannot do until its own temperature is more than that of the substance receiving heat. The plate does not transmit all the heat to the substance, because it conducts some through its thickness to other places; therefore assuming the temperature as an average for the case cited equal 343° F., it is impossible for any harm to come to the plate surface, even though the actual temperature of the surface of the plate on the furnace side is 348 × 2 = 696° F., because the film of gas is presumedly at a low temperature on the plate side, and on the other side, say, 696° F.

For radiant heat effect let it be supposed that a surface parallel to the surface of the fire is 7½ inches away, then 7·5 × ·0417 per cent, a previous determination, = 3·1 per cent of 1550° F., or 48° F., and it leaves 1502° F. as an assumed maximum

temperature, but this is for convected heat effect, whereas radiant effect is equivalent to six times as much, therefore inversely $48 \times 6 = 248$ taken from 1550 leaves 1302° F. But in practice the surface of a fire is taken as 2000° F., therefore $2000 - 248 = 1752°$ F. and the difference taken from 1302 leaves 1054° F.; but 328° F. of this is transferred to the water, leaving 626 as the assumed temperature of the plate surface on the furnace side; and these two determinations by their mean may give the true temperature of the plate surface, or $\frac{622 + 696}{2} = 661°$ F. Heat at this temperature cannot damage the plate strength materially, because the average temperature of the plate is 477° F., and this is in the region of what Dr. Nicolson determined by actual test.

## CHAPTER XV.

### NORMAL RESULTS OBTAINED BY ABNORMAL METHODS.

M. Petiet made some experiments on the Northern of France Railway with a Stephenson locomotive—divided into sections—though all were under the usual heat effects and methods common to ordinary practice.

This subdivision rendered accurate determinations possible, and two of the experiments require extended notice, because they form the basis for assumed improvements in boiler practice that may have an economical result in the future.

The furnace section included the first 3½ inches of all the tubes, and the total heating surface was 76·43 square feet for the furnace. Four other sections of 3 feet each gave 179 square feet of heating surface, or a total of 716 derived from 125 tubes of 1⅞ inches diameter, equal to a through area of 2·38 square feet.

The two examples referred to were both under one blast pipe pressure of 3·94 inches of water, and though the tests were made under ordinary conditions for very different heating surface and through areas—when referred to equal quantities of fuel burnt in the same time, both quantitative and economical efficiencies were practically equal.

One test was made under ordinary conditions with heating surface as given above; whilst the other

was with half of the tube ends plugged at the furnace end, making the divisions as follows: Furnace 65·9 square feet, and 358 square feet for the four tube sections; whilst the through area was only 1·19, or as 1 to 2 of the other.

The sections are numbered 1 to 5. The coke tests are marked A, briquette tests B, and plugged tubes for briquettes C.

Maximum evaporation per square foot:—

| | | | | | | |
|---|---|---|---|---|---|---|
| | | lb. | lb. | lb. | lb. | lb. |
| No. 1. | Evaporation A = | 29 | 10 | 5·2 | 2·96 | 1·88 |
| No. 2. | „ B = | 38·9 | 14 | 6·8 | 4·32 | 2·81 |
| No. 3. | „ C = | 44·7 | 21 | 10·6 | 6·34 | 4·76 |
| | | 1 | 2 | 3 | 4 | 5 |

Fuel per square foot:—

| | | | | | | |
|---|---|---|---|---|---|---|
| | | lb. | | per lb. | | |
| No. 1. | Coke A = | 80·8 | Evaporation | 7·98 | Draught | 2·36 |
| No. 2. | Briquettes B = | 108·8 | „ | 8·16 | „ | 3·94 |
| No. 3. | „ C = | 94·3 | „ | 8·11 | „ | 3·94 |

Minimum evaporation per square foot for the lowest determination:—

| | | | | | | |
|---|---|---|---|---|---|---|
| No. 4. | Evaporation A = | 26·3 | 7·9 | 3·8 | 2·12 | 1·29 lb. |
| No. 5. | „ B = | 42·9 | 9·8 | 5·1 | 3·24 | 2·36 „ |
| No. 6. | „ B = | 30·7 | 7·6 | 4·1 | 2·15 | 1·48 „ |
| No. 7. | „ C = | 30·1 | 12·8 | 6·2 | 2·37 | 2·09 „ |
| | | 1 | 2 | 3 | 4 | 5 |

Fuel per square foot:—

| | | | | | | |
|---|---|---|---|---|---|---|
| | | lb. | | lb. | | lb. |
| No. 4. | Fuel Coke A = | 72·7 | Evap. | 7·19 | Draught | 1·57 |
| No. 5. | „ Briquettes B = | 113·9 | „ | 6·82 | „ | 3·15 |
| No. 6. | „ „ B = | 82·6 | „ | 6·88 | „ | 1·57 |
| No. 7. | „ „ C = | 67·9 | „ | 6·94 | „ | 1·57 |

The best is 2 B for 8·16 lb. of water per lb. of fuel, under a draught of 3·94 inches when burning 108·8 lb. of briquettes per square foot of grate.

The next is 1 A = 7·98 lb. under a draught of 2·36. Taken as a proportion of B, it should have used a draught of 2·9 inches and burnt more fuel.

The other low evaporations were under low draught pressures except 5 B where more fuel was burnt under a draught of 3·15 inches. In this trial radiant heat was excessive as indicated by the evaporation of the furnace section, which was abnormally high.

Generally the efficiency was low, compared with other tests, and this was no doubt due to the low draught pressure.

One lesson taught is that a high consumption may occur under a low draught pressure, but it lowers efficiency and reduces evaporation. On the other hand, even under a high draught waste may occur if the heating surface is inadequate or inefficient.

Yet the trials proved that an ample draught for a restricted flue area did not destroy efficiency, this being a deduction from 3 C.

B and C are taken as examples of maximum evaporation as tables, B performance was made under ordinary conditions burning briquettes, and C burning briquettes, but with half the tubes plugged.

*Heating Surface.*

| | | | | |
|---|---|---|---|---|
| B Furnace | = 76·43 sq. ft. | Tubes | 716 sq. ft. |
| C „ | = 65·9 „ „ | „ | 358 „ „ |

Draught in both cases 3·94 inches.

The results are worked out, and are given in tabulated form for easy comparison.

Table 1 gives the evaporative value of each section in the order of 1 to 5, and these are referred to as B and C.

### TABLE I.

| | Water Evaporated per Section 1 | 2 | 3 | 4 | 5 | Fuel lb. | Efficiency lb. | Draught in. |
|---|---|---|---|---|---|---|---|---|
| B. | 38·9 | 14 | 6·8 | 4·32 | 2·18 | 108·8 | 8·16 | 3·94 |
| C. | 44·7 | 21 | 10·6 | 6·34 | 4·76 | 94·3 | 8·11 | 3·94 |

### TABLE II.

*Performance Referred to Equal Quantities of Fuel.*

| | | | | | | lb. | |
|---|---|---|---|---|---|---|---|
| B = | 33·7 | 12·1 | 5·9 | 3·75 | 2·43 | 94·3 | per sq. ft. of grate. |
| C = | 44·7 | 21 | 10·6 | 6·34 | 4·76 | 94·3 | ,, ,, ,, |

*Heating Surface of Boiler in Square Feet.*

| | | | | | | | Area Through Tubes |
|---|---|---|---|---|---|---|---|
| B. | 76·43 | 179 | 179 | 179 | 179 | = 792·43 | 2·38 sq. ft. |
| C. | 65·9 | 87·5 | 87·5 | 87·5 | 87·5 | = 423·9 | 1·19 ,, ,, |

*Water Evaporated per hour in lb.*

| | | | | | | Total |
|---|---|---|---|---|---|---|
| B. | 2584 | 2165 | 1064 | 671 | 435 = | 6919 lb. |
| C. | 3058 | 1874 | 948 | 580 | 425 = | 6885 ,, |

*Units of Heat per Section—B.Th.U.*

| | | | | | |
|---|---|---|---|---|---|
| B. | 2,971,600 | 2,489,750 | 1,223,600 | 771,650 | units |
| C. | 3,516,700 | 2,155,100 | 1,090,200 | 667,000 | ,, |

*Total Heat of Furnace and Tubes.*

| | | | | | |
|---|---|---|---|---|---|
| B. | Furnace | 2,971,600 | Tubes | 4,985,250 | units |
| C. | ,, | 3,516,700 | ,, | 4,401,000 | ,, |

*Total Heat for the Whole Boiler.*

B = 7,956,850 B.Th.U.
C = 7,917,750 ,,

The nearness of the two results, in spite of the widely different conditions, suggest several inferences, the first being that draught effect was irrespective of

the area of delivery; moreover, the nearness of the total unit value for furnace and tubes means a much better equalization of heat. But the problem is—why C performance was practically equal to B with practically only half the heating surface?

As the different values of heating surface under the same draught pressure practically produced the same efficiency, it leads to a consideration of how the blast pipe produces the result, though the discharge area from the tubes were as 1 to 2.

The blast pipe undoubtedly creates a vacuum which means the removal of part or all the substance contained in a given space. If the space is circumscribed by a spherical envelope, then at any part of the circumference if an opening is made, a gaseous substance would rush in to fill the space at a defined velocity, such velocity being in proportion to the negative pressure; but 1 square inch of opening would mean a given supply, but a larger volume moving at a double velocity would not presumedly fill the space any quicker.

Where the area of inlet is 1·19 the volume, entering at the induced velocity, would be in proportion to the area, and the space would be filled in a given time. If the area of inlet was doubled, presumedly, the space would be filled in half the time; but under no conceivable condition could a larger volume as mere bulk enter the available space.

Equal volumes may be of different weights, and where one volume is double the weight of another, as a gas it will expand to fill a given space, and where such space is occupied by an expanded volume

of a heavier gas of double the density of another, only half a volume is needed. In this way an area of 1·19 discharged half the volume of another area of 2·38; but where the half volume was equal to the weight of one volume of the larger area, the actual weights were equal.

The conditions in both cases produced an equal result under one blast pipe force. The meaning is that in both B and C trials the weight of fuel was the same, and the quantity of air admitted to the furnace must have been equal also. The slight difference in the final result was no doubt due to extra frictional resistance in the tubes and at the outlet which slightly retarded the velocity, and this would be in favour of blast pipe effect, as it would allow a little more time between the delivery of the substance into the vacuum and its discharge into the atmosphere.

It will be shown that the plugged tube trial marked the limit of draught pressure where the normal was 100 per cent of heating surface and the abnormal 53 per cent; therefore the double pressure effect was never reached, though it was closely approached.

It may not be lost time to give the *modus operandi* of the blast pipe.

Under normal conditions of working a body of gas fills the furnace tubes and smoke-box, including the chimney of a locomotive, and the inflow of air is governed by the rate of discharge; referred to equal weights the volumes are different, and where different areas of passage are allowed either the velocity is increased or the volume is condensed. In both cases inlet to the furnace was equal and dispersion to

atmosphere was equal also; therefore volume is the governing factor under constant atmospheric conditions and under a constant pressure.

Under natural draught conditions, when the gases are done with in the boiler flues they are discharged into the chimney, and thence to atmosphere, and assuming the gas is the same as the air, where 1 lb. of air, under ordinary atmospheric conditions, exists in a given volume, the same lb. of air at a higher temperature becomes a greater volume; or equal volumes differ in weight, and such difference is the moving factor in combustion.

The blast pipe, when the mouth is placed centrally below, and nearly level with the inlet to the short chimney, emits the waste steam from the exhaust of the cylinders at a considerable velocity which is proportionate to the area of the mouth, and though the weight is little, the high velocity of outflow results in a considerable force which is expended against the substance opposing its movement, and the steam expands to the space produced. The surrounding substance being so much colder, the steam is immediately condensed, resulting in a partial vacuum, and into this vacuum the gases issuing from the tube ends are projected. As they enter the negative pressure zone they expand under the heat supplied by the steam, and by expansion a further body of substance opposing it is displaced, and the resulting effect is found at some distance above the chimney, which may be assumed to extend far above the material outlet of the short projection above the smoke-box.

The expansion effect of the gas can only occur

when it has a base to act from, and this must be the whole area of the tube plate, and whether an equal weight of gas is delivered by an area of one or two it expands, certainly, to the base area, and must always exert an equal thrust pressure against the whole area of the tube plate.

Under one draught pressure the smoke-box must be under a consistent negative pressure, being less than the atmospheric condition which marks the limit rate of flow. The blast pipe constantly induces a vacuum, "that is a partial one," and the tendency of the column above the chimney is to fill it, but the air entering the furnace is making its way to the same bourne, and its rate multiplied by its weight represents its momentum, but the higher rate of the lighter gas has an equal momentum, therefore action and reaction are equal and opposite for equal areas; but the air inlet represented by the fire-bar spaces may be 6 square feet, whereas the area of the chimney may be only one-fourth of this; therefore the air effect is four times that of the other. Under equal conditions the gas from the column above the chimney would fill half of the vacuum space, therefore only half of the gaseous products would be discharged which is impossible for boiler conditions; but where the value of one is four and the other one, the gaseous products, as new product, would occupy four-fifths of the space and the above-chimney gas one-fifth still, leaving one-fifth of the new evolution undischarged which is equally impossible, but this one-fifth is merely an arbitrary value which is dealt with by the force supplied by the exhaust steam, thus preventing the

re-entry of the already discharged gas; therefore the vacuum space induced by the blast pipe is filled with recent gaseous product, and such space over the given time, being equivalent to the gaseous product over a similar time, is referred to equal conditions, and this is ample for the purposes of combustion.

Obviously an increased draught pressure can deal with an increased quantity of product, and that means a more rapid combustion of fuel in the same time.

Thus blast pipe effect deals with quantity referred to volume, under atmospheric conditions of pressure, and whether the delivery is from an area of 1 or 2, the same weight of gas delivered will, over a given time, represent an aggregate thrust value for the area of the tube plate.

Of course a given weight of gas, delivered by an area of 1 must be condensed to a suitable volume, whereas for an area of 2, only half the density would be needed. Within the conduit of 1 area the pressure must be double that within the conduit for 2 areas, but the pressure outside or at the delivery end of the conduit, is that for the 2-area delivery; therefore half the 2-area volume is represented by the 1-area volume within the conduit; but in the smoke-box it expands to the full volume, or the half volume becomes one under the governing pressure.

A numerical example will make the argument clear, as follows:—

Say, that 1·8 lb. of steam, of 20 lb. absolute pressure, passes out of the blast pipe nozzle per second, the temperature is about 228° F.

The volume, due to 1 lb. of such steam, is about

19·7 cubic feet, and 1·8 lb. = 35·5 cubic feet. When condensed by contact with the colder air the result is a space denuded of vapour of about 35 cubic feet capacity, into which the waste gases rush; but the gases as they expand to the smoke-box capacity exist at 700° F., therefore about 113 cubic feet of gas at 700° F. must be discharged per second, and as the volumes are as their absolute temperature, assuming the gas is the same as the air, then 50 cubic feet of air at 62° F. enters the furnace per second, and 113 cubic feet of gas at 700° F. leaves the end of the tubes in the same time for the open tube trial, and for twice the density 56·5 cubic feet, say, at 1400° F. leaves the tube ends for the plugged tube trial, and 56·5 ÷ 1·19 = 47 feet per second velocity. Now, 50 cubic feet referred to the same area = 50 ÷ 1·19 = 42 feet per second velocity; therefore the outflow is 5 feet per second faster, and as this is in excess of the supply rate the discharge is always assured. Thus it is evident that the limit condition is practically reached by the plugged tube trial for the given draught.

The 113 cubic feet volume value is based on the pressure being that of the atmosphere, whereas about 4 lb. is discharged at a velocity of 47 feet per second. Now 4 lb. moved 47 feet = 308 foot-pounds of work done, and assuming this can be converted into pressure, equal 308 lb. per square foot, then 14·7 lb. per square inch × 144 square inches = 2116·8 lb. per square foot, then as (2116·8 + 308) : 2116·8 : : 113 : 98 cubic feet the actual volume to be dealt with.

Thus a vacuum space of 35 cubic feet has to deal with a volume of 98 cubic feet of gas at 700° F., or

in some way 98 cubic feet of gas for one condition is involved in 35 cubic feet for another.

The space, presumedly, originally held 35 cubic feet of air at 62° F. under 14·7 lb. per square inch pressure, and 35 cubic feet becomes 72 cubic feet at 700° F., therefore 72 cubic feet at 700° F. is assumedly capable of being involved in 35 cubic feet of space under the vacuum conditions, leaving 26 cubic feet to be otherwise dealt with. Now this 72 cubic feet is presumedly under atmospheric pressure, but suppose it is under 16·9 lb. per square inch, or 2424·8 lb. per square foot. If allowed to expand to the 14·7 lb. pressure the volume becomes 82 cubic feet; therefore 72 cubic feet of gas out of 98 cubic feet is accounted for, under the assumed conditions of 16·9 lb. per square inch. This may be accounted for by the action of the steam velocity, aided by the fact that the outflow velocity from the tubes is 5 feet per second ahead of the inflow to the furnace.

As a result 73·4 per cent of the discharge is due to the vacuum, and 5 per cent due to the excess velocity of outflow to inflow, leaving 21·6 per cent to the credit of the steam velocity making a total of 100 per cent, and roughly speaking the original argument is sustained that one-fifth of the discharge must be due to steam velocity outside of the vacuum effect.

As the examination is of a speculative character, suppose that at some height above the chimney the temperature is 80° F. and the volume under atmospheric pressure is 52 cubic feet, and when the velocity of outflow is converted into pressure the whole performance is accounted for.

It is obvious that some such condition must exist or the abnormal conditions could not be equal to the normal, and for two very dissimilar sets of proportions where trial proved that both quantitative and economical efficiencies were practically equal, the conditions examined must rule.

From the deductions arrived at, a closer examination may show that both quantitative and economical efficiency may be gained in existing plants by reasonable alterations or additions.

## CHAPTER XVI.

### ANALYSIS OF ACTUAL PERFORMANCE OF LOCOMOTIVE BOILER.

In consequence of the results obtained from two widely different trials being practically equal, the excess air measured by the gaseous products must have been equal also in both cases.

The actual trial of B, when a slightly larger amount of fuel was burnt, can make little difference when compared with C, because the efficiencies were so nearly equal; but the efficiencies are taken when burning 94·3 lb. of coal per square foot of grate, in conjunction with 50 per cent excess air.

With 9 square feet of grate the products of combustion are about 14,427 lb. per hour, and assuming the gas to be the same as the air the volume at 62° F. = 183,222 cubic feet; therefore about 51 cubic feet of air or 4 lb. of gas of ·243 specific heat = ·97 units of heat are required to increase the temperature 1° F.

Based upon M. Peclet's rule the fire surface temperature is about 1956° F., and convected heat is estimated to equal 6,619,257 units, equal to 1841 units per 51 cubic feet of gas due to the combustible, and 62° F. × ·97 = say 60 units brought in with the air; or about 1901 units contained in 4 lb. of gas of 51 cubic feet volume at 62° F.

As a general deduction C is credited with 545,100 units in excess of B for the furnace section. The

about relative values for the two trials gave C about 13 per cent advantage over B for the furnace section, and B was 11·6 per cent better for the other sections.

Therefore C has an apparent gain of 13 per cent at the furnace end, and a loss of 11·6 per cent at the other, or 1·4 per cent gross in favour of C.

This is but a rough estimate, still it is within ·5 per cent of that actually determined.

Assuming the smoke-box end of the tubes for B trial discharges 113 cubic feet of gas at 700° F., the velocity of discharge $= 113 \div 2{\cdot}38 = 47{\cdot}5$ feet per second, whereas, for a free velocity for C, $113 \div 1{\cdot}19 = 95$ feet per second, such rates being for equal volumes and weights. For a fire surface temperature of 1956° F., the second volume becomes 235 cubic feet, and the velocities, free on entering the tubes, are for B 98·7 feet per second, and C 197·4 feet per second for equal volumes and weights.

As a deduction from the results the final velocities in both cases must be practically equal, therefore C volume must be condensed one-half, due to only half the through area, otherwise the equal results could not be attained.

Now, assuming half of the initial volume, or 117·5 cubic feet, enters the tubes of C, and for a free velocity under atmospheric pressure the temperature is 744° F., because $(62 + 461) : (744 + 461) :: 51 : 117{\cdot}5$ cubic feet (the new volume). The volume is increased from 51 to 117·5 by the addition of 682° F. equivalent to $682 \times {\cdot}97 = 661{\cdot}5$ B.Th.U., but during its expansion work was done equal to a movement through 66·5 feet, or $117{\cdot}5 - 51 = 66{\cdot}5$. The movement was made against a pressure of 14·7 lb.

per square inch, and 14·7 × 144 ÷ 772 = 182 heat units, because the basis is an area of 1 square foot; therefore of the 661·5 units, 182 units were utilized in doing work, leaving 479·5 units to sustain the increased temperature. The total heat in 4 lb. of gas, including that of atmosphere, equal 744 × ·97 = say 722 units.

Now, suppose 117·5 cubic feet of gas is held as a constant volume whilst the temperature is raised to 1956° F. or through 1212° F., then 1212 × ·97 = 1176 units + 722 = 1898 units, or within three units of 1901 as previously calculated. This is easily accounted for because the gas is a little more than 4 lb. weight, therefore the units of heat required so nearly represent the temperature that 1901 units is still the value.

The ratio of the specific heats for the two performances are as 1 to 1·34, and referred to the temperature of 1178 and worked out; 1879 units of heat were used in increasing the temperature leaving 299 otherwise employed.

A balance sheet of the assumed heat values referred to their assumed functions is accounted for as follows:—

| | Units. |
|---|---|
| Heat utilized in raising the temperature from 62 to 744° F. | = 479·5 |
| Heat utilized in increasing the volume from 51 cubic feet to 117·5 | = 182·0 |
| Heat utilized in increasing the temperature from 744 to 1956° F. | = 879·0 |
| ,, otherwise utilized | = 299·0 |
| ,, brought in by the air | = 60·5 |

making a total of 1901 B.Th.U. if fully worked out.

Thus it appears that the whole performance rests upon this 1901 unit determination. In C performance 545,100 units were in excess of that credited to B, and these were used up in the furnace evaporation, equal 151·4 units per second. The probability is that this heat was due to compression, because the envelope was incapable of retaining the excess temperature, therefore the condition is just as if the gas was a sponge from which heat was squeezed out by pressure, therefore the temperature is still 1956° F., and the gas still holds 1901 units referred to 1 second's supply of heat, but the volume is 117·5 cubic feet for C, and twice that for B, for 4 lb. of gas in both cases, though the volumes are as 1 to 2.

Taking the final temperature as 700° F., then 700 × ·97 = 682·5 units carried away in the waste gases, leaving 1218·5 units × 3600 seconds = 4,386,600 units, leaving 14,400 units, equal 4 units per second, therefore the temperature of the waste gases must be 704° F.

The difference between 1956 and 704 = 1252° F. × ·97 = 1214·4 units.

Obviously the same difference can occur between a higher initial temperature and a higher final, or by a lower initial and a lower final, but the temperature estimated is probably correct.

Two conditions are evident for the C performance, i.e. the volume of gas must be one-half of that for B, under the assumed double compression for equal temperatures, and secondly the restricted tube heating surface must transmit double the quantity of heat.

As a result the gases given off by the fire must be formed under double pressure for C, yet the half

volume of double the density must involve the same number of heat units as B for double the gaseous volume, where both performances are under one temperature.

Where 51 cubic feet weighs 4 lb., and 113 cubic feet weighs the same, the volume ratio is as 1 to 2·2, and assuming the fire-grate openings = 2·5 square feet, then the ratio of fire-grate openings to tube-openings is as 2·2 to 1, or $2·5 \div 1·19 = 2·1$, or practically a balance between compression and air influence.

Doubling the pressure doubles the resistance, and also the force to overcome it; but 51 cubic feet of gas weighs 1·8 lb. and doubling the pressure halves the volume, and two such volumes compressed to 51 cubic feet will weigh 3·6 lb.; therefore under the double pressure effect the force of the air is as 4, and the resistance as 3·6, leaving a preponderance of 10 per cent in favour of air force to ensure movement.

Frictional resistance is offered to the passage of the gas through the tubes, but a dense gas offers no more resistance than a light weight gas, therefore, the resistance in both cases may be said to be equal for equal surfaces. Though, probably, the condensed performance had the greater friction.

The velocities are in proportion to their head heights from which the velocity is derived, and $8\sqrt{51} = 56·8$ feet per second, and $113 \div 2 = 56·5$ and $8\sqrt{56·5} = 60$ feet per second, and bearing in mind the retarding effect of frictional resistance, it is safe to say that C performance was the maximum, in which the discharge velocity was a little ahead of the supply

velocity, or about 10 per cent; therefore the frictional resistance is practically a negligible amount, because 10 per cent is practically the force value to ensure movement when the gases are entering the tubes, and this is again an illustration of the fact that velocity can be converted into pressure, and pressure is equivalent to dead weight.

This speculative analysis agrees closely with what practice demonstrates as referred to C trial. Thus it substantiates what has been said in regard to blast-pipe action.

A few deductive points arise out of the examination, all going to prove the correctness of the speculative method adopted.

Taking the head velocities of the gas and air at the front end of the boiler performance as percentage values, the gas is 100 and the air 94, or where 100 led, 94 must follow, but referred to volume velocity where 51 cubic feet = 100, and 47 cubic feet, or 94 for the gas. The superior air volume of superior weight is as 100, therefore it was superior as a driving force to 94 as a resistance, thus the results found are supported by the conditions, or the gross advantage is 6 per cent.

One other variation must be noticed, namely the slower outlet velocity of the B performance, or 42 feet per second for B and 47 feet per second for C.

The cause is unquestionably frictional resistance which was bound to be greater in B case, due to the double heating surfaces, and the value is 4·8 per cent, but C must have been under frictional resistance to half the value, or 2·4 per cent, which is accounted for in both cases in the final velocity.

Now 47 × .4 lb. = 188 foot-pounds, and 51 × 4 = 204 foot-pounds, or a difference of nearly 8 per cent, and the nearness qualifies the other references in regard to its closeness to the absolutely maximum performance of the C trial.

The question of radiant and convected heat acting together to give an evaporative result is important because such is the general idea, but it does not appear to be true, even in the exceptional case under consideration.

The extra, say 159 units per second excess evaporation factor due to an excess of 545,100 units for the hour's performance, could not be due to convected heat, because it has all been accounted for, therefore it must have been radiant, and the equal rates of consumption in both trials precludes the idea of excess fire surface temperature due to a thicker fire.

Now, doubling the pressure under which the gases were evolved causes an increase of temperature in the gaseous products, and this is due to actual work being done, though it does not add to the volume it increases the pressure, and as a result heat is added to the fire surface, and the result is an excess quantity of radiant heat.

This opens out one of the problems of combustion, but the result of the C trial, as analysed, showed no problem, or a careful examination revealed the cause from which the effect was possible.

Nothing was gained by the experiment beyond showing that the rate of transmission is contingent on draught pressure, and a suitable area of flues which has a limit for a given draught, but it does establish the fact that gases during the progress of

ordinary working, can be retarded by compressing the volume, and thereby increasing its temperature and adding to its transmission rate. Yet from the trial many lessons may be learnt by deduction, one of which is the great advantage of radiant heat acting directly or indirectly on the flue surface beyond the bridge in internal fluid boilers.

A representation of a furnace of a locomotive is shown in Fig. 18, showing how radiant heat is directed into the mouths of the tubes from the irregular surface of the fire from the facts of incandescent fuel, and it

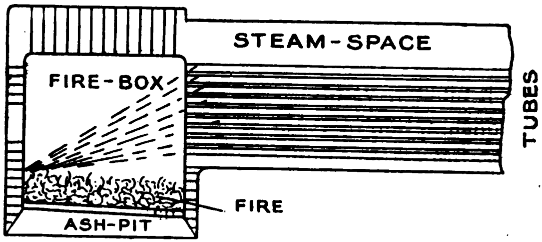



Fig. 18.—Locomotive furnace.

reveals the cause of the high efficiency found in the first few inches of the tubes in a multitubular boiler, and the first few feet of the flues in a Lancashire. The figure explains itself by showing the direct action of the rays of radiant heat, as the slanting lines.

In a locomotive boiler all the furnace-heating surface is in contact with water, whereas in boilers of the Cornish and Lancashire type much of the heating surface labours under many serious disadvantages, particularly in regard to the ends of the fire, where no heating surface exists and the consequence is that radiant heat is lost. The trial of C

merely proved that it was possible to keep up both quantitative and economic efficiency with only about half the usual heating surface. One of the deductive lessons learnt is that, if 40 per cent more fuel is burnt on an equal grate area by increasing the draught and reducing the area of outlet to the chimney, and the observance of a few other matters, the quantitative efficiency will be in proportion to the fuel burnt, whilst the fuel efficiency will be retained.

To meet the case the dryback, wing, and return flues should be reduced in area if the full benefit is to be gained. These are merely suggestions arising out of the examination of the effects produced in the abnormal trial of C, and they serve the useful purpose of drawing attention to a phase in boiler economy that has not received the attention it merits.

Some light is thrown upon the subject by experiments carried out with the marine Scotch type. Miller found many years ago that burning equal amounts of fuel on grates 10·3 and 13·75 square feet, always showed an increased efficiency of 5 per cent for the smaller grate and thicker fire, and the reason has been given.

Dr. Richardson tried the effect of 9, 12, and 14 inch fires, and found the thick fire always an advantage, because the thick fire not only showed a greater evaporation, but was more economical for equal amounts of coal burnt.

A number of very important tests were made to find what was the best width for the fire-bar spaces to prevent the loss of small coal without curtailing the air supply. About ½ inch was found to give good results, though to-day narrower spaces are used to

allow small coal to be burnt, and it can be done successfully with the aid of mechanical stokers.

In marine practice 36 to 40 lb. of coal are burnt per square foot of grate, and the draught used is about 3·9 inches of water pressure, but in many cases 19 inches of water pressure are used when large quantities of coal can be burnt, but with a great loss of efficiency.

The raking funnels in steamships are intended to aid the draught, but whether it does or not the speed induces a negative pressure behind the funnel, which is of great advantage in adding to the draught effect.

The locomotive gets its enormous evaporation power from the blast pipe, but it is aided by the speed of running which forces air into the ash-pit, therefore the locomotive is influenced by both induced and forced draught, and to these effects the boiler gets its high quantitative efficiency.

Closed stokeholds and closed ash-pits, compressing air and delivering it into the chimney, are amongst the methods used where large quantities of fuel are burnt, but not always with economy. Generally, where an efficiency of 10·77 lb. of water per lb. of coal is obtained, doubling the consumption reduces the evaporation per lb. of coal to 7·03 lb. of water, or 35 per cent of economical efficiency is wasted; but cases are known where forcing the draught has given 16 h.p. in place of 8 h.p.

The Admiralty have tested the effect of increased draughts from 2 to 6 inches. At 6 inches the evaporation has been doubled, but efficiency fell from 8·1 lb. to 7·03, equal a loss of 15 per cent. These tests were made with a Thornycroft boiler in a torpedo boat, and it established the fact that, as practice exists,

and as quantitative efficiency is gained, economical efficiency is lowered.

Cases exist where economy as well as quantity is important, and the possibility of getting both has been proved.

For land purposes 12 lb. of coal for ·75 inches of water draught is about the maximum, whereas 14 lb. on ½ inch draught pressure is possible in the navy, therefore the effect of movement to increase the draught is evident.

Martin found when burning three times the amount of fuel on a draught pressure of 1½ inches of water in the smoke-box, 6 per cent loss in efficiency occurred. Thus it is quite obvious that increasing the draught adds to the pressure on the gaseous products, because an increased velocity must meet a greater resistance, and by restricting the outlet area the increased velocity meets with a greater resistance, and velocity is resolved into pressure, whereby the gases get hotter, transmit more heat, adding to volume, whilst restricted area of outlet increases economic efficiency.

The naval engineer has done this by using retarders at the entrance to the tubes and has found a benefit, though he has attributed it to another, and probably erroneous, cause.

Ellis & Eave's system raises the temperature of the air to nearly that of steam heat, and gets an efficiency of 75 per cent. Howden's, where air at ½ and ¾ inches of water pressure is forced into the ash-pit after passing it through a heater placed in the smoke-box, is highly efficient and economical. With a heater in the smoke-box the through area is reduced and the discharge must be at a higher velocity, and

where such is converted into pressure the gases in the tubes are compressed, and more heat is transmitted, resulting in greater economy. Thus by restricting the through way area under the given pressure we might obtain the result without the heater.

# CHAPTER XVII.

## MOVEMENT OF GASES THROUGH TUBES.

THE previous generalization brings to the front the question of velocity as a means of increasing the pressure on a gas, and Professor Nicolson's drastic assertion that engineers and scientists are wrong, and have been wrong all along the line in regard to the effect of movement of the gaseous products in boiler practice, calls for more than a mere notice, because its importance is too great to be ignored under any circumstances, but coming from such an authority it must be faced.

The general idea is that a gas passing through a tube is subject to frictional resistance, but whether the gas is merely under atmospheric pressure or a higher pressure, density does not increase frictional resistance, and this deduction is accepted.

Dr. Nicolson may have been in error in attributing the results he obtained by experiment, for the reason that he appears to have ignored the value of the combustion chamber effect on the flue behind it, and in a similar way he ignored the fact of a higher furnace value for the conditions, and credited everything to the restricted flue area. In a sense the annular flue area reduction undoubtedly caused the compression of the gaseous product under the high-

draught pressure, but he appears to have assumed a free velocity as the true cause, whereas such was impossible, though the calculated velocity had an influence on the pressure the gas was subjected to, where velocity was converted into pressure.

His experiment deserves attention, because it showed what could be done, though it did not prove that, in practice, his ideas should be carried out.

The trials in the Northern of France Railway, and the learned Professor's, both show the benefit of a restricted flue area. In Dr. Nicolson's experiment he reduced the through area to one-tenth of the original whilst practically doubling the heating surface, which necessitated a very high-draught pressure. Increasing the pressure acting on a gas under usual boiler conditions, must increase the quantity of water evaporated in a given time, and to get such a pressure, economically, the outlet area must be restricted.

In gunnery practice a high velocity projectile, of equal weight to another for a lower velocity, has the advantage in regard to perforating or striking ability. After the object is struck all velocity disappears, but the weight of the projectile is the same. The act of striking destroys velocity, but only by converting it into pressure, and the higher velocity gives the greater pressure for one weight of projectile.

Heat has no weight neither has it mass, yet it can act upon, or influence a body that has. Thus, what occurs to the body is due to the heat effect. In boiler practice heat is the cause of all that occurs. In a previous chapter the question of the limit capability of a plate to transmit heat was examined, and the conclusion was that the plate was

merely a convenience in separating that which had heat to give away from a substance that wanted it; whilst the substance receiving heat was benefited by rapid circulation over the heated part. The fact is that gases give heat away very slowly, therefore they must have time to give away heat to another substance.

The contention of Dr. Nicolson is that a rapidly-moving gas gives away more heat than a slow-moving gas.

Now, the gaseous products from combustible fuel, are produced generally, under atmospheric pressure conditions, and where a given weight is produced per second an equal weight must be got rid of in the same time or the new evolution cannot take place.

Compressing a gas increases its temperature, and whatever the proportionate temperature so is roughly the rate of transmission; therefore increasing the temperature is wise economy in boiler practice.

Merely accelerating the speed of gaseous products through the flues of a boiler by increasing the temperature will account for a greater volume. Burning more fuel in a given time increases the gas volume, but the greater velocity only permits unit volumes to remain in contact a less time than a slower, where the original outlet is not restricted. The increased velocity of discharge must result in a condensing effect due to increased resistance, but the increased velocity over the flue surfaces also means a greater frictional resistance in proportion to the square of the velocity; therefore part of the extra draught will be used up in overcoming it, and as this may be more than the advantage gained by the velocity effect in

densifying the gas a loss results. Practical experience proves this by revealing the cause, hence merely increasing the draught pressure to burn more fuel loses quantitative value and is therefore against efficiency.

Restricting the area of outlet from the flues alters the effect and is advantageous. The restricted outlet reduces velocity, by increasing it on the outlet side which is lost to expansion, and decreases it on the inside. Decreasing velocity by opposing the progress of the elastic gas, tends to make it expand backwards, but the incoming air at the velocity set by the discharge from the chimney is many times heavier for a unit volume; therefore the gas' is obstructed by the restricted outlet, and is also driven by the heavier air volume, and between the two it is compressed.

The velocity of discharge from the chimney as efficient area gives that by which the volume is driven out, and it sets the rate, and such rate cannot be exceeded, commencing at the air inlet to the fire and finishing at the outlet from the chimney. The inlet admits substance at 62° F. and the substance from the flues on the chimney side must be at chimney temperature. The volumes are as their absolute temperatures; therefore the areas of inlet and outlet must be as their volumes consistent to the velocity. If the gas is condensed from 1 volume to half a volume when it passes the outlet to the chimney it will expand to the chimney conditions, and it can only do this by thrusting a volume equal to the expanded volume from the mouth. The thrusting volume expands to the conditions of the chimney both for density and temperature.

Before it expands; that is before it passes out of the outlet to the chimney, it must be under compression, and that means a higher temperature, and such excess temperature is felt all the way back to the surface of the fire, and therefore increased temperature is due to pressure; therefore the new gases given off from the fire are produced under the excess pressure. For double the amount of fuel burnt, presumedly double the gaseous volume is discharged, otherwise combustion could not proceed.

In the flues the gases are accelerated because the discharge is increased; but the gases are generated under compression effect due to the restricted flue outlet. Thus compression increases the temperature, not only of the products but of radiant heat; therefore evaporation is carried on under a higher temperature and at a greater rate.

Whatever may be said to the contrary, the velocity of the gases through the flues cannot be faster than the respective areas will allow, proportionate to the velocity of discharge from the chimney to atmosphere.

It is quite needless to pursue the subject at greater length, because the whole matter is so obvious to those interested as to appear unnecessary to mention. Enough has been said to direct attention to a matter that is of wide-world interest wherever steam plants are used.

*Chimney Draught.*—As a conclusion to an interesting subject something must be said about chimney draught for natural conditions because many strange ideas appear to exist, and perhaps many plants are less efficient than they should be due alone to an

improper knowledge of chimney proportions. A few points have already been noticed; therefore the present will be practical applications that experience has taught.

A 50 feet chimney of 50 cubic feet capacity will discharge, theoretically, 2·18 lb. per second, and a 100 feet 3·09 lb.; therefore doubling the height of a chimney only adds 46 per cent to its discharge value. Below $\frac{1}{2}$ inch of water pressure no chimney can do even fair work. Another fact is pertinent, viz. as a rough assertion, the actual discharge from a chimney is only about half of the theoretical. Many rules are given for finding the draught value of a chimney; but they all labour under the disadvantage of an excessive constant factor.

A good rule is as follows; amended to fit in with practice.

T = absolute temperature of the chimney gases in F°.

A = area of chimney top inside, in square feet.

H = height of chimney above grate level.

Q = quantity of coal burnt per square foot of grate, in lb.

The amended formula is as follows:—

$Q = 1100\ A\ \sqrt{H \times (T - 523)}$, or for 100 feet chimney.

$$Q = 1100\ 8\ \sqrt{100 \times 861 - 523}$$

$$= \frac{8800 \times 183}{861} = 1893 \text{ lb.}$$ This is the amount of coal that can be burnt with a chimney 100 feet high for an outlet area of 8 square feet = 236 lb. of coal per square foot of outlet.

The following are given as mere proportions for

50 feet high per lb. of coal 1·27 square inches, for
200 „ „ „ „ „ ·63 „ „
or for four times the height the area is reduced one half.

For 100 feet per lb. of coal ·95, and ·236 × ·95 = 227 square inches, say 2 square feet. This is only approximate.

In practice about 140 cubic feet of air is allowed per lb. of fuel, and chimney proportions are based on this value.

Chimneys taper towards the top, and by direct experiment when a tall chimney was cut down to 80 per cent, or 60 feet less than the original, it was better than the original height, because the area was enlarged. In general practice the taper is 1 in 12. This means about ·3 inches per foot, and the thickness down to 25 feet must be 9 inches when the diameter does not exceed 4 feet. Anything more than this the thickness must be 14½ inches for the top 25 feet, and half a brick thicker for every 25 feet downwards. The London Building Acts insist upon 20 feet for the extra half brick thickness.

The quantity of gas, by weight, discharged by a chimney in a given time rests upon area, height, and velocity of flow and density. The velocity increases nearly as the square of the temperature; but there is a temperature where the gas discharged is maximum. This is found at about 600° F.; but between 400° F. and 600° F. the difference is only 4 per cent, for which reason 400° F. is the most economical taking in every condition.

Draught is independent of area, but is dependent on the difference in weight of equal columns of gas

in the chimney at its temperature, and air outside at atmospheric temperature. When burning anthracite coal $1\frac{1}{4}$ inches of water pressure is needed, and 200 feet high will supply it; whereas bituminous coals are served with a chimney 75 feet high.

The actual area of outlet is not measured across from brick to brick, but it refers to an area less by about 44 per cent.

Plenty of rules exist by which the true area can be found, but for all practical purposes where the area required is assumed to be 44 per cent of the brick-to-brick measurement of area it is approximately close.

Short chimneys require some kind of forced draught to aid the natural draught effect. Plenty of chimneys have gases much higher than 600° F. admitted to them, but where that occurs the boilers are at fault, for which reason many water-heating apparatus are installed to utilize some of the extra heat, but a restricted outlet to the flue will in most cases prevent the evil.

Much more could be said on the subject, but with the points given it is possible for those who wish for higher efficiency to get it without any exercise of extreme ingenuity.

THE END.

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